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RESEARCH ARTICLE

Estimation of carbon stocks in the forest plantations of Sri Lanka†

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Abstract: Forest plantations have the ability to sequester carbon in their biomass and reduce the rate of increase of atmospheric carbon dioxide. Therefore, plantation forestry forms an important option for mitigating global warming and consequent climate change. The objective of the present study was to estimate the biomass and carbon stocks of the existing forest plantations in Sri Lanka. Height and diameter measurements of the trees at breast height from 22 monocultures and 51 mixed-cultures, established and maintained by the Forest Department, were obtained from the FORDATA data base and used to calculate the existing carbon stocks using allometric relationships.

The total estimated monoculture C stock in 2008 amounted to 4.23 million metric tons in an area of 57618.8 ha. Around 89% of this total C stock in monocultures is contributed by five tree species, namely, *Pinus caribaea* (44%), *Tectona grandis* (21%), *Eucalyptus grandis* (11%), *Eucalyptus camaldulensis* (7%) and *Swietenia macrophylla* (6%), occupying 92% of the area. Total C stock in mixed cultures in 2008 amounted to 0.681 million tons in 5949.6 ha. Five mixed cultures, i.e. *Eucalyptus robusta* and *E. grandis* (17%), *Pinus* mixed (13%), *E. grandis* and *E. microcorys* (12.5%), *Eucalyptus* mixed (7%) and *Acacia mangium* and *A. auriculiformis* (5%), contributed to 55% of this C stock. Monocultures, which showed the highest per ha C stocks were *Pinus caribaea* in Badulla (205 t ha^{-1}) and Nuwara Eliya (164 t ha^{-1}) and *Eucalyptus grandis* in Ratnapura (197 t ha^{-1}) and Nuwara Eliya (168 t ha^{-1}). Mixed plantations of *Acacia decurrens* and different species of *Eucalyptus* grown in Nuwara Eliya showed the highest combined per ha C stocks ranging from 226 – 279 t ha^{-1}. The maximum per ha C stock in some of the Sri Lankan forest plantations in different climatic zones were either on par or above the benchmark average C stock values specified by the IPCC for the respective climatic zones. Age distribution of the monoculture C stocks showed that the highest percentage (i.e. 39%) was in the 21-30 year plantations, followed by the 31-40 year plantations (32%).

Keywords: Carbon sequestration, climate change mitigation, forest biomass, tropical forests.

INTRODUCTION

In Sri Lanka, forest plantations have been established since 1880s to meet the increasing demand for timber and fuelwood, with soil conservation in important watersheds being an additional benefit (Pushparajah, 1987; Sahajananthan, 1987). Almost all the existing plantations have been established after the 1950s and consist of fast-growing exotic trees such as species of *Eucalyptus*, *Pinus* and *Acacia* along with teak and mahogany (Vivekanandan, 1987). In addition to their industrial timber products, the importance of forest plantations has increased substantially during the last two decades, in view of the increased awareness on global climate change and the role of forests in regulating the global carbon cycle (Dixon *et al.*, 1994; Clark *et al.*, 2003; Clark, 2004a; Houghton, 2005). Forests have the ability to absorb large quantities of atmospheric carbon dioxide for their photosynthesis and sequester carbon in their biomass (Chambers *et al.*, 2001). As carbon dioxide is the principal greenhouse gas contributing to the enhanced greenhouse effect (Houghton, 1997) and the consequent global warming, which drives climate change, forests have the potential to reduce the rate of global warming and the resultant climate change (Brown *et al.*, 1996; Cannell, 1996; Sathaye & Ravindranath, 1998; Malhi & Grace, 2000; White *et al.*, 2000; Schulze *et al.*, 2000; Baker *et al.*, 2004; Grace & Meir, 2009; Lewis *et al.*, 2009). However, increasing deforestation of natural forests, especially in the tropics, is reducing the global warming mitigation potential of tropical forests and threatens to convert them from a significant global carbon sink to a net carbon source (Clark, 2002; 2004b, 2007; Lewis, 2006). Therefore, plantation forestry forms an important option for climate change mitigation (IPCC, 2007; Nabuurs *et al.*, 2007).

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The carbon sequestration potential of a forest is determined by its biomass production. While the rate of biomass production (i.e. increase of forest biomass per year) indicates the potential of a forest to absorb atmospheric CO_2 and reduce global warming within a given time period, the standing biomass of a forest indicates how much carbon has been sequestered during its lifetime. Although Sri Lanka contains nearly 65,000 ha of forest plantations, their carbon stocks as indicated by the standing biomass, have not been estimated. The published research literature on the growth of plantation forest species in Sri Lanka reports only the height and diameter at breast-height (dbh) increments over relatively short periods of time at a limited number of locations (Vivekanandan, 1979; Phillips & Weerawardena, 1991a, b, c, d; Weerawardena & Phillips, 1991a, b). Therefore, the objective of the present work was to estimate the total carbon (C) stocks of plantation forests in Sri Lanka and examine the contribution from different tree species in different locations and climatic zones.

Estimates of C stocks will enable economic valuation of Sri Lankan plantation forests to explore possibilities of financial gains through mechanisms such as the United Nations Reducing Emissions from Deforestation and Degradation in Developing Countries Programme (UN-REDD) (Gibbs *et al.*, 2007; Ravels, 2008; Schwartzman *et al.*, 2008). C stock estimates could also form the basis for analysis of benefits and costs of afforestation or reforestation with forest plantations in quantifying their climate change mitigation potential (Sathaye *et al.*, 2001; 2007; Strengers *et al.*, 2007; Benítez-Ponce *et al.*, 2008). Quantification of the species-wise distribution of C stocks in different geographical regions of Sri Lanka will lead to identification of regions, which are rich or deficient in C stocks while providing information on specific tree species, which have greater C sequestration potential under their respective climatic and soil conditions. Furthermore, comparative estimates of total biomass, on which C stock estimates are based, provide indications of the condition of forest plantations in a given climatic zone or division and give an indirect estimate of its site quality (Clark *et al.*, 2001; Houghton & Goodale, 2004).

METHODS AND MATERIALS

***Data source*:** The FORDATA database maintained by the Forest Department was used for this study. The FORDATA contains height and diameter at breast height (dbh) measurements for 22 monocultures and 51 mixed-cultures, which have been established and maintained by the Forest Department. These forest plantations are distributed over 17 forest divisions, which are largely based on administrative districts, covering all three major climatic zones (i.e. Wet, Intermediate and Dry Zones). The database lists 86363.8 hectares (ha) of forest plantations in the country. However, calculations were done only for 63568.4 ha, which were under the age of 50 years by 2008. The remaining 22795 ha, which are over the age of 50 were assumed as having been harvested by 2008. The lists of monoculture and mixed-culture plantation forest tree species that were used for the calculations and their distribution are given in Tables 1 and 2 respectively.

The database describes the location of each plantation in terms of division, range, beat, block and sub-block and also gives the area (ha), slope, altitude, number of stems per ha, diameter at breast height (cm), height (m), planting year of the plantation and the last surveyed year with reference to each sub-block. These specifications are given by a single record of the database. The plant species is indicated by a code. Records of the same species in different places in the database were filtered using the Microsoft Office filter tools.

Table 1: List of monoculture plantation forest tree species used in the calculations

Sequential no.	Species code	Species
1.	1	*Tectona grandis*
2.	2	*Swietenia macrophylla*
3.	28	*Eucalyptus deglupta*
4.	29	*Eucalyptus cloeziana*
5.	30	*Eucalyptus pilularis*
6.	31	*Eucalyptus robusta*
7.	32	*Eucalyptus citriodora*
8.	33	*Eucalyptus globulus*
9.	34	*Eucalyptus grandis*
10.	37	*Eucalyptus camaldulensis*
11.	38	*Eucalyptus tereticornis*
12.	39	*Eucalyptus microcorys*
13.	40	*Eucalyptus torelliana*
14.	49	*Acacia mangium*
15.	73	*Acacia auriculiformis*
16.	82	*Acacia melanoxylon*
17.	83	*Acacia decurrens*
18.	92	*Casuarina* sp.
19.	93	*Cupressus* sp.
20.	94	*Pinus caribaea*
21.	95	*Pinus patula*
22.	97	*Pinus oocarpa*

Table 2: List of mixed-cultures of plantation forests used in the calculations

Seq. no.	Species code	Species composition
1.	1_2	*Tectona grandis* & *Swietenia macrophylla*
2.	1_37	*Tectona grandis* & *Eucalyptus camaldulensis*
3.	1_73	*Tectona grandis* & *Acacia auriculiformis*
4.	1_86	*Tectona grandis* & *Kaya* sp.
5.	1_87	*Tectona grandis* & *Eucalyptus:Tectona mixture*
6.	2_94	*Swietenia macrophylla* & *Pinus caribaea*
7.	31_34	*Eucalyptus robusta* & *Eucalyptus grandis*
8.	31_39	*Eucalyptus robusta* & *Eucalyptus microcorys*
9.	31_42	*Eucalyptus robusta* & *Eucalyptus* mixed
10.	31_83	*Eucalyptus robusta* & *Acacia decurrens*
11.	32_34	*Eucalyptus citriodora* & *Eucalyptus grandis*
12.	31_95	*Eucalyptus robusta* & *Pinus patula*
13.	33_34	*Eucalyptus globulus* & *Eucalyptus grandis*
14.	33_83	*Eucalyptus globulus* & *Acacia decurrens*
15.	34_37	*Eucalyptus grandis* & *Eucalyptus camaldulensis*
16.	34_39	*Eucalyptus grandis* & *Eucalyputs microcorys*
17.	34_42	*Eucalyptus grandis* & *Eucalyptus* mixed
18.	34_49	*Eucalyptus grandis* & *Acacia mangium*
19.	34_83	*Eucalyptus grandis* & *Acacia decurrens*
20.	34_93	*Eucalyptus grandis* & *Cupressus* sp.
21.	34_94	*Eucalyptus grandis* & *Pinus caribaea*
22.	34_95	*Eucalyptus grandis* & *Pinus patula*
23.	34_98	*Eucalyptus grandis* & *Pinus* mixed
24.	37_38	*Eucalyptus camaldulensis* & *Eucalyptus tereticornis*
25.	37_40	*Eucalyptus camaldulensis* & *Eucalyptus torelliana*
26.	37_49	*Eucalyptus camaldulensis* & *Acacia mangium*
27.	37_73	*Eucalyptus camaldulensis* & *Acacia auriculiformis*
28.	37_86	*Eucalyptus camaldulensis* & *Kaya* sp.
29.	37_94	*Eucalyptus camaldulensis* & *Pinus caribaea*
30.	38_40	*Eucalyptus tereticornis* & *Eucalyptus torelliana*
31.	39_93	*Eucalyptus microcorys* & *Cupressus* sp.
32.	39_94	*Eucalyptus microcorys* & *Pinus caribaea*
33.	40_49	*Eucalyptus torelliana* & *Acacia mangium*
34.	42_49	*Eucalyptus mixed* & *Acacia mangium*
35.	42_83	*Eucalyptus mixed* & *Acacia decurrens*
36.	42_93	*Eucalyptus* mixed & *Cupressus* sp.
37.	42_94	*Eucalyptus* mixed & *Pinus caribaea*
38.	42_95	*Eucalyptus* mixed & *Pius patula*
39.	42_98	*Eucalyptus* mixed & *Pinus* mixed
40.	49_73	*Acacia mangium* & *Acacia auriculiformis*
41.	73_94	*Acacia auriculiformis* & *Pinus caribaea*
42.	82_93	*Acacia melanoxylon* & *Cupressus* sp.
43.	83_94	*Acacia decurrens* & *Pinus caribaea*
44.	83_95	*Acacia decurrens* & *Pinus patula*
45.	93_95	*Cupressus* sp. & *Pinus patula*
46.	93_98	*Cupressus* sp. & *Pinus* mixed
47.	94_95	*Pinus caribaea* & *Pinus patula*
48.	34_41	*Eucalyptus grandis* & *Eucalyptus paniculata*
49.	1_42	*Tectona grandis* & *Eucalyptus* mixed
50.	42	*Eucalyptus* mixed
51.	98	*Pinus* mixed

***Calculation methodology for monoculture forest plantations*:** The calculation methodology used in this work is in accordance with the 'Good Practice Guidance for Land Use, Land Use Change and Forestry' as promoted by the IPCC (IPCC, 2003; Somogyi *et al.*, 2007) and is based on the well-established conventional techniques of forest inventory (Watson *et al.*, 2000; Brown, 2002). Calculations started at the sub-block level.

Calculation of wood volume

Initially the wood volume was calculated using the dbh and height measurements of the FORDATA database with one of the following three methods:

(a) using volume functions that have been developed for particular species

The wood volumes of six tree species (i.e. *Eucalyptus robusta*, *E. grandis*, *E. microcorys*, *Pinus caribaea*, *Tectona grandis* and *Cupressus* spp.) were calculated using available volume functions (Table 3) (Anonymous, 1996).

(b) using an estimated form factor for those *Eucalyptus* and *Pinus* species for which volume functions are not available

The following general allometric relationship was used to estimate the merchantable wood volume of species for which specific volume functions have not been developed:

$$V = f\,g\,h \qquad ...(1)$$

Where, V is merchantable wood volume per tree (m^3), g is basal area per tree (m^2) and h is tree height (m). Basal area, g, (m^2) was calculated from diameter at breast height, d, (cm) as,

$$g = (\pi d2)/40000 \qquad ...(2)$$

In equation 1, f is known as the 'form factor', which is a quantitative index of the trunk form of a particular tree species. A perfectly cylindrical trunk would have a form factor of 1. Depending on the deviation of the actual trunk form from a perfectly cylindrical form, the f value decreases from 1. Therefore, the f value had to be estimated for those species, which did not have established volume functions.

An established volume function can be considered as a widely-applicable allometric relationship for a given species. Using the available height and dbh data at the sub-block level, the volume functions of Table 3 were inverted (equation 3) to obtain form factors (f) for *Eucalyptus robusta*, *E. grandis*, *E. microcorys* and *Pinus caribaea* as 0.320, 0.335, 0.335 and 0.370, respectively:

$$f = V / g\,h \qquad ...(3)$$

For the other species of *Eucalyptus* and *Pinus* without established volume functions, form factors were 'designed' based on the estimated form factors given above. The arithmetic average of the estimated

Table 3: Known volume functions and their specifications

Species	Volume function	Specifications
Cupressus spp.	$V=[0.336929+5.574551/(\pi d)]*(\pi d^2h/40000)$	Under bark, to 5 cm cut off
Eucalyptus robusta	$V=[0.337277-(0.151178/(\pi d)]*(\pi d^2h/40000)$	Under bark, to 5 cm cut off
Eucalyptus grandis	$V=[0.337277-(0.151178/(\pi d)]*(\pi d^2h/40000)$	Under bark, to 5 cm cut off
Eucalyptus microcorys	$V=[0.296384+(2.6326592/(\pi d)]*(\pi d^2h/40000)$	Under bark, to 5 cm cut off
Pinus caribaea	$V=0.0000575*d^{1.87185}*h^{0.91418}*(1- 49.933*d^{-2..83174})$	Over bark to 5 cm cut off
Tectona grandis	V=exp(-9.7327+2.055*ln d + 0.773*ln h)	Over bark to 5 cm cut off

Note: V = Merchantable wood volume per tree (m^3); d = Diameter at breast height (cm); h = Total tree height (m)

Source: Forest Inventory Manual for Sri Lanka (Anonymous, 1996).

form factors of *Eucalyptus robusta*, *E. grandis* and *E. microcorys* (i.e. 0.330) was taken as the form factor for the other *Eucalyptus* species, which did not have volume functions. This procedure of 'designing' form factors makes the implicit assumption that the tree form does not vary significantly within a given genus. As *Pinus caribaea* was the only *Pinus* species for which a volume function was available, the form factor estimated based on its volume function (i.e. 0.370) was taken as the form factor for the rest of the *Pinus* species, which did not have volume functions.

(c) using an assumed form factor for species (other than those of *Eucalyptus* and *Pinus*), which did not have established volume functions

For the rest of the plantation forest tree species, which did not have established volume functions, merchantable wood volume per tree was calculated by equation 1, using an assumed form factor of 0.5.

***Calculation of above-ground tree biomass and carbon stock per ha*:** The merchantable tree volume that was calculated as above was converted to above-ground biomass per tree using the following relationship (Cost *et al.*, 1990):

$$\text{Above-ground tree volume } (m^3) = 1.67^* \text{ Merchantable wood volume } (m^3) \quad ...(4)$$

The factor 1.67 in equation 4 takes into account the biomass contained in leaves, branches and other above-ground parts, which are excluded when merchantable wood volume is taken.

The following formula was used to convert the above-ground tree volume (m^3) to above-ground tree biomass (kg) assuming a wood density of 490 kg m^{-3} (Birdsey, 1992):

$$\text{Above-ground biomass per tree (kg)} = \text{Above-ground tree volume } (m^3) \times 490 \text{ (kg } m^{-3}) \quad ...(5)$$

Above-ground tree biomass per ha was calculated as,

$$\text{Above-ground tree biomass per ha (kg } ha^{-1}) = \text{Above-ground per biomass tree (kg)} \times \text{No. of trees per ha} \quad ...(6)$$

Assuming the carbon content of biomass to be 50% (Sampson, 1992), the above-ground C stock per ha was calculated as,

$$\text{Above-ground C stock per ha (kg } ha^{-1}) = \text{Tree biomass per ha (kg } ha^{-1}) \times 0.5 \quad ...(7)$$

***Development of age vs above-ground C stock relationships*:** Age of each forest plantation was calculated from the difference between the surveyed year and the planted year. Relationships were developed between age and above-ground C stock per ha for each tree species at the division level. The relationships were either logarithmic or second-order polynomial and were of the following forms:

$$\text{Above-ground C stock (kg } ha^{-1}) = a \log_e (\text{Age}) + b \quad ...(8)$$

$$\text{Above-ground C stock (kg } ha^{-1}) = a + b\,(\text{Age}) + c\,(\text{Age})^2 \quad ...(9)$$

where, age is given in years. In these relationships, a pair of (age, above-ground C stock per ha) values represented one data point. After examining the initially-developed relationships, divisions having similar relationships were pooled on to a common relationship. On the other hand, when there was high variation within a given division, separate relationships were developed for different ranges within a division. Altogether 64 different relationships were developed for different species, divisions and ranges.

***Prediction of C stocks per ha in 2008*:** The developed relationships were used to predict the above-ground carbon stocks per ha in 2008 at the respective sub-block levels.

***Conversion of above-ground C stocks to total C stocks per ha*:** The significant amount of C stored in the below-ground biomass of trees has to be accounted for in any calculation of C stocks. Using a conversion factor developed by Birdsey (1992), the total C stocks per ha in 2008 were calculated as,

$$\text{Total C stock per ha in 2008} = \text{Above-ground C stock per ha in 2008} \times 1.3054 \quad ...(10)$$

Therefore, in equation 10, root biomass is taken as 30.54% of the above-ground biomass giving a root-weight ratio (i.e. ratio between root biomass and total biomass) of 0.234.

***Calculation of total C stock at the sub-block level and up-scaling*:** The total carbon stock in each sub-block in 2008 was calculated by the product between the respective total carbon stock per ha and the plantation area of the sub-block. The respective sub-block carbon stocks were cumulated over beat, range and division levels. All plantations, which were over 50 years of age by 2008, were considered as felled and were excluded from the calculation.

***Calculation methodology for mixed-culture forest plantations*:** The FORDATA database includes the total number of trees per ha in mixed plantations without specifying the ratio of the two species. Therefore, for each mixed culture, calculations were first done for individual species using the methodology outlined above. Subsequently, the total carbon stocks were calculated by assuming a 50:50% species ratio.

RESULTS

Total C stocks of monoculture forest plantations in 2008

Table 4 shows the calculated total C stocks of monoculture forest plantations of Sri Lanka in 2008. The total estimated monoculture C stock in 2008 amounted to 4.23 million metric tons. Around 89% of this total C stock in monocultures is contributed by five tree species, namely, *Pinus caribaea* (44%), *Tectona grandis* (21%), *Eucalyptus grandis* (11%), *Eucalyptus camaldulensis* (7%) and *Swietenia macrophylla* (6%). Out of the 22 monoculture species, contribution of 9 species to the total C stock exceeded 1%. In addition to those already listed, these 9 species included *Acacia auriculiformis*, *Acacia mangium*, *Eucalyptus robusta* and *Eucalyptus tereticornis*.

Age distribution of the monoculture C stocks (Figure 1) showed that the highest percentage (i.e. 39%) was in the 21–30 year plantations, followed by the 31– 40 year plantations (32%). The lowest percentage of monoculture C stocks (i.e. 0.93%) was in the young forest plantations of less than 10 years. This is primarily because of the lower carbon sequestration capacity of the young plantations, which are in the early lag phase of their growth curves.

The five species, which had the highest contribution to the total C stock were also the five species, which had the highest planted area, covering around 92% of the 57618.8 ha of monoculture forest plantations (Table 4). However, it is interesting to note that eventhough *Tectona grandis* occupied 35% of plantation area, its contribution to the total C stock was only 21%. In contrast, *Pinus caribaea* contributed 44% to the total C stock while occupying only 25% of the area. This meant a wide difference between the average C stock per ha of the two species, with *Pinus caribaea* having a much greater value (130.19 t ha^{-1}) than *Tectona grandis* (42.70 t ha^{-1}). While the inherent species variation in the efficiency of photosynthesis and biomass production process could probably have contributed to the above variation in carbon sequestration ability, the more favourable environmental conditions, particularly the greater water availability, in the areas where *Pinus caribaea* is grown (i.e. the Wet Zone) in comparison to the areas where *Tectona grandis* is grown (i.e. Dry and Intermediate Zones) would also have had a significant influence on this contrasting difference in C sequestration. The C sequestration capacity of different tree species used in monoculture plantations, as indicated by the mean C stock per ha, showed a wide variation between the 22 species, ranging from 26.25 t ha^{-1} for *Eucalyptus camaldulensis* to 190.71 t ha^{-1} for *Pinus oocarpa*, which is planted in only a very small area (Table 4).

Distribution of C stocks of the major monoculture forest plantation species by division

Pinus caribaea: *Pinus caribaea* is the species, which has the highest contribution to the total C stock of monoculture plantations. Table 5 shows the distribution of *Pinus caribaea* plantations in different divisions along with their respective productivities and total C stocks. Nearly 50% of the total C stock of *Pinus caribaea* is contributed from the divisions of Badulla and Kandy, which traverse the Wet and Intermediate Zones of Sri Lanka. Nuwara Eliya (Wet Zone), Ratnapura (Wet and Intermediate Zones) and Matale (Wet and Intermediate Zones) also contributed to a further 34% combined. Badulla showed the highest per ha C stocks followed by Nuwara Eliya, Matale and Kandy. Among the five divisions making major contributions, Ratnapura showed the lowest per ha C stocks.

More than half of the C stocks (i.e. 56%) of *Pinus caribaea* are in plantations in the 21–30 year age group (Figure 2a). This is followed by plantations in the 31–40 year age class, holding 41% of C stocks. This means that more than 95% of C stocks of *Pinus caribaea* are held in plantations within the 21– 40 year age class. There are no *Pinus caribaea* plantations which are younger than 10 years, reflecting the absence of any new plantings of this species during the decade leading up to 2008.

***Tectona grandis*:** *Tectona grandis* makes the second highest contribution (20%) to the total C stocks behind *Pinus caribaea*. Divisions Kurunegala and Moneragala, which traverse the intermediate and dry zones, provided the highest contributions (26% and 21%, respectively) to the total C stock from *Tectona grandis* (Table 6). These

Table 4: Calculated total C stocks of monoculture forest plantations of Sri Lanka in 2008

Species	Total C stock (t)	% of total	Planted area (ha)	% of total area	Mean C stock (t ha^{-1})
Pinus caribaea	1871784.85	44.296	14377.20	24.952	130.19
Tectona grandis	866178.47	20.498	20286.90	35.209	42.70
Eucalyptus grandis	462990.64	10.957	3488.50	6.054	132.72
Eucalyptus camaldulensis	315328.69	7.462	12014.70	20.852	26.25
Swietenia macrophylla	261616.98	6.191	2680.90	4.653	97.59
Acacia auriculiformis	119854.39	2.836	1375.40	2.387	87.14
Acacia mangium	93571.92	2.214	845.50	1.467	110.67
Eucalyptus robusta	85639.23	2.027	577.40	1.002	148.32
Eucalyptus tereticornis	59725.82	1.413	878.20	1.524	68.01
Pinus patula	39484.13	0.934	517.90	0.899	76.24
Eucalyptus microcorys	24101.48	0.570	207.50	0.360	116.15
Casuarina spp.	13452.76	0.318	231.50	0.402	58.11
Eucalyptus torelliana	5518.57	0.131	69.60	0.121	79.29
Eucalyptus pilularis	1640.46	0.039	9.00	0.016	182.27
Pinus oocarpa	1430.30	0.034	7.50	0.013	190.71
Acacia decurrens	1052.48	0.025	7.50	0.013	140.33
Cupressus sp.	670.70	0.016	24.50	0.043	27.38
Eucalyptus citriodora	651.07	0.015	7.50	0.013	86.81
Eucalyptus cloeziana	409.24	0.010	5.80	0.010	70.56
Eucalyptus globulus	242.62	0.006	3.80	0.007	63.85
Eucalyptus deglupta	134.33	0.003	1.00	0.002	134.33
Acacia melanoxylon	111.89	0.003	1.00	0.002	111.89
Total	4225591.01		57618.80		

Table 5: Distribution of C stocks of *Pinus caribaea* in different divisions and their productivity

Division	Per ha C stock (t ha^{-1})	Planted area (ha)	% of total area	Total C stock (t)	% of total C stock
Badulla	204.79	2413.3	16.79	494208.94	26.40
Galle	60.46	656.1	4.56	39670.16	2.12
Gampaha	81.91	68.4	0.48	5602.84	0.30
Hambantota	120.51	236.4	1.64	28487.76	1.52
Kalutara	85.14	1042.5	7.25	88762.29	4.74
Kandy	131.49	3345.4	23.27	439895.29	23.50
Kegalle	111.78	73.2	0.51	8182.30	0.44
Matale	148.52	1248.6	8.68	185445.49	9.91
Matara	90.52	1477.1	10.27	133700.01	7.14
Monaragala	31.95	2.0	0.01	63.89	0.00
Nuwara Eliya	164.01	1528.7	10.63	250725.97	13.40
Ratnapura	86.21	2285.5	15.90	197039.90	10.53
Total		14377.2		1871784.85	

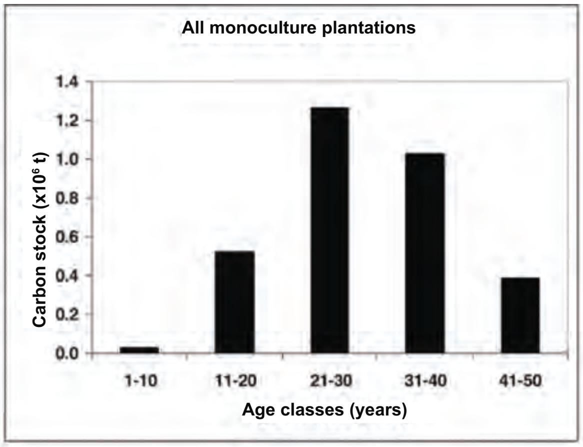

Figure 1: Distribution of monoculture carbon stocks in forest plantations of different age classes

are followed by Puttalam (14%) and Anuradhapura (11%) showing the preference of *Tectona* for drier environments. Other divisions in the Dry Zone such as Hambantota and Polonnaruwa also provided appreciable contributions to the total C stock from *Tectona*, with 8% and 6% respectively. However, the highest productivity (i.e. per ha C stock) of *Tectona* (132 t ha^{-1}) is shown in the Wet Zone division of Gampaha. Among the divisions traversing the Dry and Intermediate Zones, Hambantota had the highest productivity (82 t ha^{-1}) followed by Kurunegala and Moneragala (both ~54 t ha-1). The lowest productivity of 12 t ha^{-1} was shown in a small (20.8 t ha^{-1}) plantation in Badulla. Among the larger plantations of *Tectona*, the lowest productivity of 23 t ha^{-1} was in Ratnapura.

In contrast to *Pinus caribaea* (Figure 2a) and the overall monoculture C stocks (Figure 1), more than 87% of the C stocks in *Tectona grandis* were in plantations within the age class of 31–50 years (Figure 2b), with the stocks distributed almost equally between the two age groups of 31– 40 years and 41–50 years. This reflects the slower growth and carbon sequestration of *Tectona* in comparison to the faster growing species of *Pinus*, *Eucalyptus* and *Acacia*.

Eucalyptus grandis**:** Carbon stocks in *Eucalyptus grandis* contributed 11% to the total C stock from plantation forests, which is the third largest behind *Pinus caribaea* and *Tectona grandis* (Table 4). Table 7 shows that more than 90% of C stocks of *Eucalyptus grandis* is located in two divisions, namely, Nuwara Eliya (71%) and Badulla (22%). Both these divisions are at high elevations with Nuwara Eliya in the Wet Zone and Badulla in the Intermediate Zone. Productivity of *E. grandis* in Nuwara Eliya (168 t ha^{-1}) is twice as that in Badulla (83 t ha^{-1}), probably because of the greater water availability in the Wet Zone. Although Hambantota, Kandy and Ratnapura showed higher per ha C stocks than Nuwara Eliya, the planted extents in these divisions were very small. Therefore, these high productivities may not be representative of the entire division. However, they

Table 6: Distribution of C stocks of *Tectona grandis* in different divisions and their productivity

Division	Per ha C stock (t ha^{-1})	Planted area (ha)	% of Total area	Total C stock (t)	% of total C stock
Ampara	46.24	615.0	3.03	28439.29	3.28
Anuradhapura	27.15	3443.9	16.98	93484.99	10.79
Badulla	11.85	20.8	0.10	246.56	0.03
Gampaha	131.72	160.4	0.79	21127.68	2.44
Hambantota	82.37	850.5	4.19	70058.39	8.09
Kandy	32.15	51.2	0.25	1645.97	0.19
Kurunegala	54.36	4117.1	20.29	223813.39	25.84
Matale	35.52	1509.2	7.44	53611.75	6.19
Monaragala	53.81	3426.0	16.89	184337.93	21.28
Polonnaruwa	32.68	1704.6	8.40	55702.28	6.43
Puttlam	31.30	3939.8	19.42	123334.80	14.24
Ratnapura	23.14	448.4	2.21	10375.44	1.20
		20286.9		866178.47	

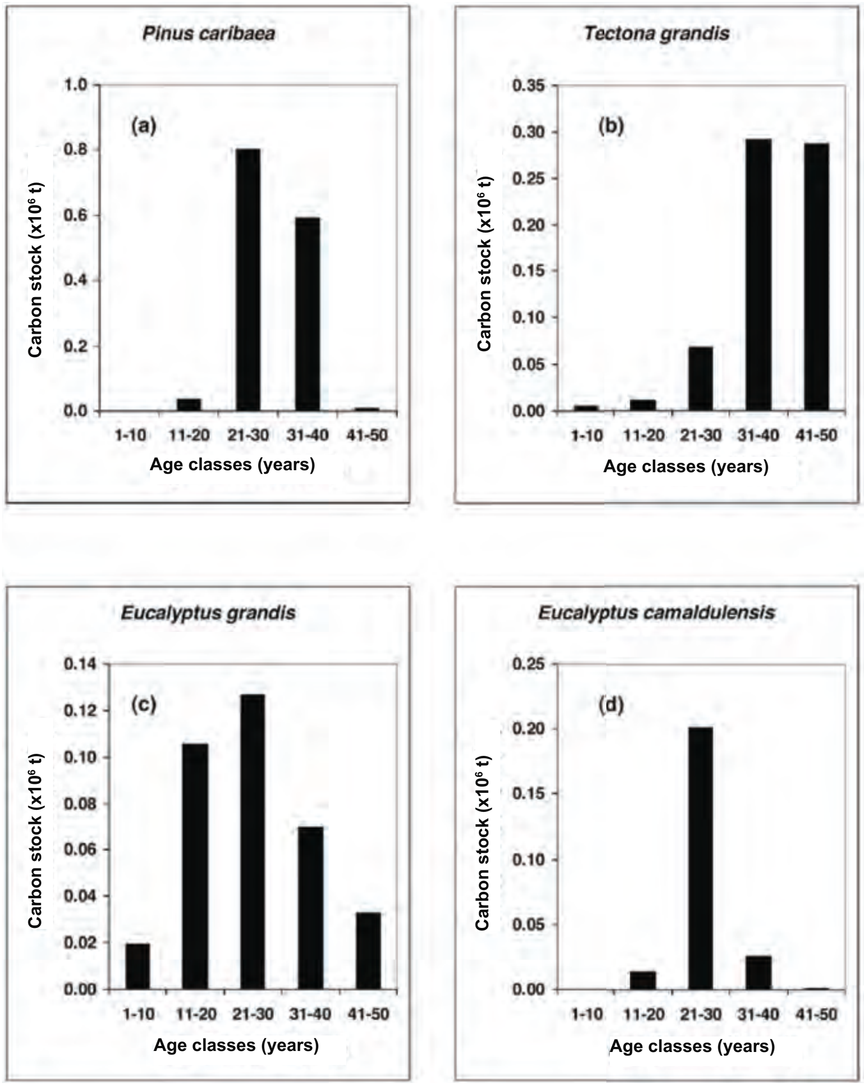

Figure 2: Distribution of monoculture carbon stocks in forest plantations of different age classes of (a) *Pinus caribaea*; (b) *Tectona grandis*; (c) *Eucalyptus grandis* and (d) *Eucalyptus camaldulensis*

probably indicate the upper limits of productivity for *Eucalyptus grandis* under the climatic conditions found in these divisions.

Productivity of *E. grandis* in Nuwara Eliya and Kandy (Table 7) were comparable to the productivity levels of *Pinus caribaea* in Nuwara Eliya and Badulla (Table 5). Interestingly, both species showed high productivities in Hambantota although the planted areas were relatively small. In contrast, in Badulla, which had extensive areas planted with both species, *Pinus caribaea* had a substantially greater productivity than *E. grandis*.

Similar to *Pinus caribaea* and the overall monoculture C stocks, *E. grandis* also had the highest percentage of its C stocks (i.e. 36%) in the 21–30 year-old plantations (Figure 2c). However, the next highest C stocks (30%) were in the younger plantations within the 11–20 year age class. Hence, the majority of C stocks of *E. grandis* was in the plantations of 11–30 year age group. Furthermore,

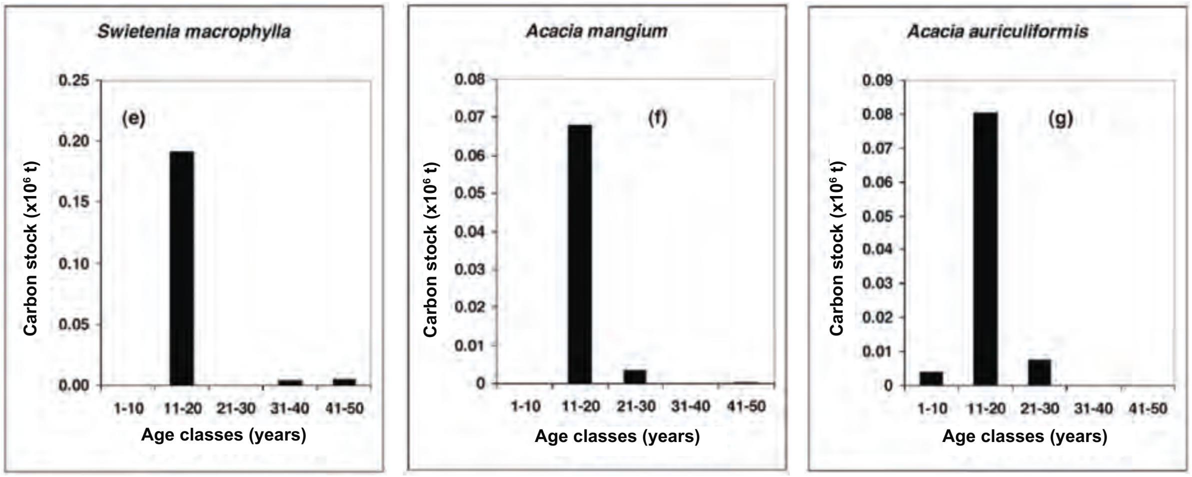

Figure 2 (Contd.): Distribution of monoculture carbon stocks in forest plantations of different age classes of (e) *Swietenia macrophylla*; (f) *Acacia mangium and* (g) *Acacia auriculiformis*

Table 7: Distribution of C stocks of *Eucalyptus grandis* in different divisions and their productivity

Division	Per ha C stock (t ha^{-1})	Planted area (ha)	% of total area	Total C stock (t)	% of total C stock
Anuradhapura	72.97	9.6	0.28	700.53	0.15
Badulla	83.22	1207.2	34.61	100463.85	21.70
Hambantota	175.72	1.5	0.04	263.58	0.06
Jaffna	104.83	41.7	1.20	4371.25	0.94
Kandy	187.94	2.0	0.06	375.88	0.08
Kurunegala	91.07	83.2	2.38	7576.80	1.64
Matara	139.81	19.3	0.55	2698.30	0.58
Monaragala	82.38	138.5	3.97	11409.97	2.46
Nuwara Eliya	168.46	1962.7	56.26	330640.11	71.41
Ratnapura	196.95	22.8	0.65	4490.36	0.97
Total		3488.5		462990.64	

5.6% of *E. grandis* C stocks were in the youngest age group of less than 10 year - old plantations, reflecting a clear shift from *Pinus caribaea* to *E. grandis* in the reforestation/afforestation programmes of the last two decades leading up to 2008.

***Eucalyptus camaldulensis*:** *Eucalyptus camaldulensis* contributes 7.5% to the total C stocks from forest plantations (Table 4). More importantly, it occupies nearly 21% of the area of forest plantations. In contrast to *E. grandis*, which is predominantly distributed in Nuwara Eliya and Badulla (Table 7), *E. camaldulensis* is more widely distributed (Table 8) with 58% of its C stock being distributed in the Dry Zone divisions of Polonnaruwa, Puttalam, Hambantota, Anuradhapura, Moneragala and Ampara. A further 16% is located in Kurunegala, which traverses the Intermediate and Dry Zones. Badulla and Matale, which traverse the Intermediate and Wet Zones, are the other divisions with significant contributions to the total C stock of *E. camaldulensis*, with 17% and

9.5%, respectively. It is notable that in all divisions, irrespective of their climatic zone, the productivity of *E. camaldulensis*, as indicated by per ha C stocks (12 – 43 t ha^{-1}), was much lower than that of *E. grandis* (73 – 197 t ha^{-1}) (Table 7). *Tectona grandis*, which was better adapted to climatic conditions in the Dry and Intermediate Zones, also had a greater range of per ha C stocks (12 – 132 t ha^{-1}) (Table 6) than *E. camaldulensis*. This lower productivity of *E. camaldulensis* explains the disproportionality between its planted area (21% of the total area of plantation forests) and its contribution to the total C stock (7.5%).

The large majority (i.e. 83%) of C stocks of *E. camaldulensis* are in plantations within the 21–30 year age group (Figure 2d). However, the younger plantations contained only 5.6% of the C stocks of this species, with none in plantations younger than 10 years. This indicates that *E. camaldulensis* has not been a preferred species in reforestation/afforestation programmes undertaken during the last two decades leading up to 2008.

Table 8: Distribution of C stocks of *Eucalyptus camaldulensis* in different divisions and their productivity

Division	Per ha C stock (t ha^{-1})	Planted area (ha)	% of total area	Total C stock (t)	% of total C stock
Ampara	41.67	157.2	1.31	6551.09	2.08
Anuradhapura	12.73	860.0	7.16	10944.27	3.47
Badulla	43.04	1219.7	10.15	52500.54	16.65
Galle	11.81	2.5	0.02	29.52	0.01
Gampaha	14.73	10.5	0.09	154.67	0.05
Hambantota	14.85	1908.2	15.88	28337.02	8.99
Kandy	40.62	7.6	0.06	308.70	0.10
Kurunegala	38.46	1277.2	10.63	49119.68	15.58
Matale	42.72	697.8	5.81	29807.16	9.45
Matara	15.13	14.4	0.12	217.87	0.07
Monaragala	14.41	643.5	5.36	9276.03	2.94
Polonnaruwa	42.47	2006.5	16.70	85210.48	27.02
Puttlam	13.36	3209.6	26.71	42871.67	13.60
Total		12014.7		315328.69	

Table 9: Distribution of C stocks of *Swietenia macrophylla* in different divisions and their productivity

Division	Per ha C stock (t ha^{-1})	Planted area (ha)	% of total area	Total C stock (t)	% of total C stock
Anuradhapura	87.12	6.0	0.22	522.73	0.20
Gampaha	105.27	74.7	2.79	7863.58	3.01
Hambantota	101.83	10.7	0.40	1089.63	0.42
Kalutara	106.49	0.7	0.03	74.55	0.03
Kegalle	97.91	63.3	2.36	6197.97	2.37
Kurunegala	97.85	2373.7	88.54	232268.04	88.78
Puttlam	82.67	40.8	1.52	3372.82	1.29
Ratnapura	92.14	111.0	4.14	10227.66	3.91
Total		2680.9		261616.97	

Swietenia macrophylla**:** *Swietenia macrophylla* contributes 6% to the total C stock from forest plantations while occupying 4.5% of the planted area (Table 4). Nearly 90% of both the planted area and the C stock is located in Kurunegala (Table 9). Per ha C stocks of *Swietenia macrophylla* varied within the narrow range of 83 – 106 t ha^{-1} in the different divisions in which it is distributed, irrespective of their climatic conditions. More than 95% of C stocks of *Swietenia macrophylla* are in plantations of the 11–20 year age group (Figure 2e).

***Acacia mangium* and *A. auriculiformis*:** These two *Acacia* species contribute 5% to the total C stock from plantation forests while occupying nearly 4% of the planted area (Table 4) and are distributed in several divisions across all climatic zones (Tables 10 and 11). Nearly 50% of the C stock from *A. mangium* came from three Wet Zone divisions, Kegalle, Kandy and Kalutara with 20%, 17% and 13%, respectively. In *A. auriculiformis*, Matale, Ratnapura and Anuradhapura provided the major contributions to the C stock with 27%, 20% and 14%, respectively. In addition, Kegalle also

Table 10: Distribution of C stocks of *Acacia mangium* in different divisions and their productivity

Division	Per ha C stock (t ha^{-1})	Planted area (ha)	% of total area	Total C stock (t)	% of total C stock
Anuradhapura	52.84	41.2	4.87	2176.94	2.33
Badulla	74.41	114.8	13.58	8542.09	9.13
Gampaha	162.62	27.6	3.26	4488.35	4.80
Kalutara	161.53	76.7	9.07	12389.02	13.24
Kandy	166.32	93.2	11.02	15500.64	16.57
Kegalle	154.29	120.1	14.20	18530.37	19.80
Kurunegala	54.88	60.6	7.17	3325.59	3.55
Matale	54.32	44.5	5.26	2417.39	2.58
Puttlam	52.54	85.0	10.05	4465.61	4.77
Ratnapura	119.56	181.8	21.50	21735.91	23.23
Total		845.5		93571.92	

Table 11: Distribution of C stocks of *Acacia auriculiformis* in different divisions and their productivity

Division	Per ha C stock (t ha^{-1})	Planted area (ha)	% of total area	Total C stock (t)	% of total C stock
Gampaha	87.64	68.9	5.01	6038.71	5.04
Ratnapura	79.39	307.3	22.34	24397.91	20.36
Polonnaruwa	93.08	52.0	3.78	4839.90	4.04
Kurunegala	90.45	89.4	6.50	8085.88	6.75
Anuradhapura	91.76	187.0	13.60	17159.87	14.32
Puttlam	91.03	97.1	7.06	8838.74	7.37
Hambantota	85.92	28.1	2.04	2414.48	2.01
Matale	88.96	367.1	26.69	32657.07	27.25
Kandy	90.73	20.0	1.45	1814.51	1.51
Kalutara	88.45	10.0	0.73	884.47	0.74
Kegalle	85.68	148.5	10.80	12722.86	10.62
Total		1375.4		119854.39	

provided 11% to the total C stock from *A. auriculiformis*. Per ha C stocks of *A. mangium* were clearly greater in the Wet Zone divisions with a range of 154 – 166 t ha^{-1} (in Gampaha, Kegalle, Kandy and Kalutara) as compared to 53 – 74 t ha^{-1} in divisions located in Intermediate and Dry Zones (i.e. Anuradhapura, Badulla, Kurunegala, Matale and Puttalam). In contrast, *A. auriculiformis* had a much narrower range of productivities (i.e. 79 – 93 t ha^{-1}) in all divisions in which it is grown, irrespective of the climatic conditions.

More than 95% and 87% of C stocks of *A. mangium* and *A. auriculiformis* were contained in plantations in the 11-20 year age group (Figures 2f and 2g). In fact, more than 99% of all C stocks of both these *Acacia* species were in plantations of 30 years or younger. These data also indicated a clear shift in the species preference in reforestation/afforestation programmes from *Pinus caribaea* to *Acacia* species during the last two decades.

Total C stocks of mixed culture forest plantations in 2008

Table 12 shows the C stocks of the component species and total C stock of all mixed culture forest plantations. Total C stock in mixed cultures in 2008 amounted to 0.681 million tons. In terms of planted area, the mixed cultures were only 10% of the area of monoculture plantations. However, the mixed cultures had a proportionately greater total C stock with 16% of that of monocultures. This is because of the greater per ha C stocks of mixed cultures with an overall mean of 114.54 t ha^{-1} as compared to 73.34 t ha^{-1} (Table 4) in monocultures.

There were five mixed cultures, which contributed more than 5% to the total C stock from mixed cultures. They were *Eucalyptus robusta* & *E. grandis* (17%), *Pinus* mixed (13%), *E. grandis* & *E. microcorys* (12.5%), *Eucalyptus* mixed (7%) and *Acacia mangium* & *A. auriculiformis* (5%). These five mixed cultures accounted for 55% of the total C stock from mixed cultures while occupying 44% of the total area of mixed culture plantations. 69% of the C stock of the mixed cultures in 2008 resides in *Eucalyptus*-based mixed plantations. Mixed plantations based on *E. grandis* accounted for 46% of total mixed culture C stocks, while mixtures based on *E. camaldulensis* accounted for 5%. Apart from *Eucalyptus*-based mixed plantations, mixed cultures based on *Tectona grandis* accounted for 9% of the total C stocks in mixed cultures. Three species of *Acacia* (i.e. *A. mangium*, *A. auriculiformis* and *A. decurrens*) were also major contributors to C stocks in mixed plantations with mixtures involving *Acacia* contributing for 20.5%. Likewise, mixed plantations involving *Pinus caribaea* and *P. patula* contributed nearly 25% of the total C stock from mixtures.

Distribution of C stocks of the major mixed culture forest plantation species by division

Mixed plantations involving *Eucalyptus grandis*: All mixed plantations involving *E. grandis* are located in Nuwara Eliya and Badulla divisions. These plantations contain nearly 46% of the total C stock from mixed cultures with a total C stock of 313,123 t (Table 13). Out of this, 75% is located in Nuwara Eliya while 25% is in Badulla. The productivities (i.e. per ha C stocks) of both *E. grandis* and its associated species were appreciably greater in Nuwara Eliya when compared to Badulla. For *E. grandis*, respective mean productivities were 89 and 48 t ha^{-1} respectively for Nuwara Eliya and Badulla. This reflected more favourable growing conditions in Nuwara Eliya for *E. grandis* as well as its associated species. When compared with the respective productivities of monoculture plantations of *E. grandis* in Nuwara Eliya and Badulla (i.e. 168 and 83 t ha^{-1} respectively-Table 7), its productivities in the mixed cultures, where *E. grandis* was only 50% of the total tree population were slightly greater. Interestingly, on average, *E. grandis* provided a greater share of the total C stock of the mixtures in Badulla (i.e. 57%) as compared to those in Nuwara Eliya (52%).

The specific mixtures which provided the highest contributions to the total C stock in *E. grandis*-based plantations in Nuwara Eliya and Badulla were *E. grandis* & *E. robusta* (36%), *E. grandis* & *E. microcorys* (15.5%) and *E. grandis* & *Acacia decurrens* (10%), which were all in Nuwara Eliya, and *E. grandis* & *E. microcorys* (12%), which was in Badulla (Table 13). The species, which showed the highest productivities in association with *E. grandis* were *Acacia decurrens* (119 t ha^{-1}), *E. globulus* (101 t ha^{-1}) and *E. microcorys* (84%), all in Nuwara Eliya, and *E. robusta* (73 t ha^{-1}) in Badulla.

Mixed plantations involving *Eucalyptus camaldulensis* and *Tectona grandis*: Mixed plantations involving *E. camaldulensis* contain 8.2% of the total C stock in mixed cultures (Table 12). These plantations are distributed mainly in the dry and intermediate zones (Table 14). Nearly 41% of the C stocks of mixed cultures involving *E. camaldulensis* were in the mixture with *E. tereticornis* in Badulla while mixtures with *Tectona grandis* in Ampara, Moneragala, Kurunegala, Puttalam and Polonnaruwa accounted for 36%. In all divisions except Puttalam and Polonnaruwa, productivity of *E. camaldulensis*, which ranged from 4.8 – 23.8 t ha^{-1}, was lower than its associated species, which ranged from

Table 12: Calculated total C stocks of mixed culture forest plantations of Sri Lanka in 2008

Species composition of the mixture	Total C stock of spp. 1 (t)	% of Total C Stock from spp. 1	Mean carbon stock of spp. 1 (t ha^{-1})	Total C stock of spp. 2 (t)	% of total C stock from spp. 2	Mean carbon stock of spp. 2 (t ha^{-1})	Total C stock of mixture (t)	% of total mixed C stock	Planted area (ha)	% of planted area
Eucalyptus robusta & *E. grandis*	58040.89	50.00	65.54	58040.89	50.00	65.54	116081.8	17.03	885.6	14.89
Eucalyptus grandis & *E. microcorys*	51907.84	61.03	87.95	33151.87	38.97	56.17	85059.71	12.48	590.2	9.92
Acacia mangium & *A. auriculiformis*	23426.51	65.45	83.16	12364.79	34.55	43.89	35791.30	5.25	281.7	4.73
Eucalyptus grandis & *A. decurrens*	12729.69	40.18	79.76	18954.94	59.82	118.77	31684.63	4.65	159.6	2.68
Tectona grandis & *Eucalyptus mixed*	2807.92	10.70	14.09	23428.71	89.30	117.55	26236.63	3.85	199.3	3.35
E. grandis & *Pinus caribaea*	12111.59	46.69	34.30	13828.77	53.31	39.16	25940.36	3.81	353.1	5.93
E. camaldulensis & *E. tereticornis*	8032.94	35.22	23.84	14772.51	64.78	43.84	22805.44	3.35	337.0	5.66
Tectona grandis & *E. camaldulensis*	11646.98	57.41	20.95	8640.27	42.59	15.54	20287.25	2.98	555.9	9.34
Pinus caribaea & *Pinus patula*	8830.44	50.00	89.65	8830.44	50.00	89.65	17660.89	2.59	98.5	1.66
Eucalyptus mixed & *A. mangium*	7132.05	57.48	77.78	5275.31	42.52	57.53	12407.36	1.82	91.7	1.54
Eucalyptus grandis & *A. mangium*	4755.07	42.00	45.81	6567.81	58.00	63.27	11322.88	1.66	103.8	1.74
E. grandis & *Eucalyptus* mixed	6610.85	59.72	88.98	4459.72	40.28	60.02	11070.57	1.62	74.3	1.25
E. grandis & *Pinus patula*	7643.81	74.99	66.76	2549.93	25.01	22.27	10193.74	1.50	114.5	1.92
E. globulus & *E. grandis*	4888.67	48.22	93.83	5248.80	51.78	100.74	10137.47	1.49	52.1	0.88
Eucalyptus mixed & *A. decurrens*	4542.14	49.46	138.06	4640.49	50.54	141.05	9182.64	1.35	32.9	0.55
E. robusta & *E. microcorys*	4406.29	48.29	83.61	4718.62	51.71	89.54	9124.91	1.34	52.7	0.89
Eucalyptus torelliana & *A. mangium*	2148.24	23.92	24.61	6833.68	76.08	78.28	8981.92	1.32	87.3	1.47
Tectona grandis & *A. auriculiformis*	1255.03	16.41	7.95	6393.33	83.59	40.52	7648.36	1.12	157.8	2.65
Eucalyptus mixed & *Pinus caribaea*	5009.26	75.49	112.06	1626.33	24.51	36.38	6635.59	0.97	44.7	0.75
E. grandis & *E. camaldulensis*	3867.97	64.03	40.72	2172.71	35.97	22.87	6040.67	0.89	95.0	1.60
E. camaldulensis & *A. mangium*	809.33	14.31	8.47	4846.80	85.69	50.75	5656.14	0.83	95.5	1.61
E. camaldulensis & *A. auriculiformis*	529.89	10.52	5.55	4506.71	89.48	47.19	5036.60	0.74	95.5	1.61
E. microcorys & *Cupressus* sp.	3401.60	83.81	82.76	656.98	16.19	15.98	4058.58	0.60	41.1	0.69
Tectona grandis & *Kaya senegalensis*	570.27	15.24	3.59	3170.87	84.76	19.96	3741.14	0.55	158.9	2.67
E. microcorys & *Pinus caribaea*	1462.57	39.46	73.13	2243.46	60.54	112.17	3706.03	0.54	20.0	0.34
E. robusta & *Pinus patula*	2320.40	63.10	68.65	1357.21	36.90	40.15	3677.61	0.54	33.8	0.57
Acacia decurrens & *Pinus caribaea*	1757.83	50.31	82.53	1736.15	49.69	81.51	3493.98	0.51	21.3	0.36
E. globulus & *A. decurrens*	1194.51	41.97	103.87	1651.33	58.03	143.59	2845.84	0.42	11.5	0.19
Acacia decurrens & *Pinus patula*†	2771.07	100.00	135.17	0.00	0.00	0.00	2771.07	0.41	20.5	0.34

- continued

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Species composition of the mixture	Total C stock of spp. 1 (t)	% of total C stock from spp. 1	Mean carbon stock of spp. 1 (t ha^{-1})	Total C stock of spp. 2 (t)	% of total C stock from spp. 2	Mean carbon stock of spp. 2 (t ha^{-1})	Total C stock of mixture (t)	% of total mixed C stock	Planted area (ha)	% of planted area
T. grandis & *Eucalyptus* spp.	388.16	14.45	12.40	2298.73	85.55	73.44	2686.89	0.39	31.3	0.53
E. grandis & *Pinus* mixed	1456.14	56.16	109.48	1136.68	43.84	85.46	2592.81	0.38	13.3	0.22
E. citriodora & *E. grandis*	1000.57	53.28	30.60	877.21	46.72	26.83	1877.78	0.28	32.7	0.55
E. grandis & *E. paniculata*	943.15	51.66	37.73	882.45	48.34	35.30	1825.60	0.27	25.0	0.42
E. robusta & *Eucalyptus* mixed	801.98	44.38	86.23	1004.97	55.62	108.06	1806.95	0.27	9.3	0.16
Eucalyptus mixed & *Pinus patula*†	1629.14	100.00	135.76	0.00	0.00	0.00	1629.14	0.24	12.0	0.20
Eucalyptus mixed & *Cupressus* spp.	1483.98	91.47	148.40	138.37	8.53	13.84	1622.35	0.24	10.0	0.17
Swietenia macrophylla & *P. caribaea*	789.66	48.77	56.40	829.37	51.23	59.24	1619.04	0.24	14.0	0.24
Cupressus spp. & *Pinus* mixed	220.10	14.41	14.39	1307.81	85.59	85.48	1527.91	0.22	15.3	0.26
E. robusta & *Acacia decurrens*	469.07	36.36	82.29	820.87	63.64	144.01	1289.93	0.19	5.7	0.10
A. auriculiformis & *Pinus caribaea*	682.42	56.03	47.72	535.44	43.97	37.44	1217.85	0.18	14.3	0.24
E. camaldulensis & *Kaya* spp.	142.03	12.39	8.35	1003.96	87.61	59.06	1145.98	0.17	17.0	0.29
E. grandis & *Cupressus* spp.	1105.90	98.71	122.88	14.45	1.29	1.61	1120.35	0.16	9.0	0.15
E. camaldulensis & *Pinus caribaea*	145.62	16.48	7.55	738.19	83.52	38.25	883.81	0.13	19.3	0.32
Eucalyptus mixed & *Pinus* mixed	443.39	60.73	130.41	286.72	39.27	84.33	730.11	0.11	3.4	0.06
Tectona grandis & *Sw. macrophylla*	138.14	30.95	26.56	308.25	69.05	59.28	446.38	0.07	5.2	0.09
E. tereticornis & *E. torelliana*	133.52	50.00	66.76	133.52	50.00	66.76	267.03	0.04	2.0	0.03
Ac. melanoxylon & *Cupressus* spp.	172.07	83.91	74.81	33.00	16.09	14.35	205.07	0.03	2.3	0.04
E. camaldulensis & *E. torelliana*	14.49	11.01	4.83	117.09	88.99	39.03	131.58	0.02	3.0	0.05
Cupressus spp. & *Pinus patula*	61.69	62.48	14.35	37.05	37.52	8.62	98.74	0.01	4.3	0.07
Eucalyptus mixed	.	.	.	.	.		49012.86	7.19	620.3	10.43
Pinus mixed	.	.	.	.	.		88447.04	12.98	215.1	3.62
Total							**681466.3**		**5949.6**	

†C stock of *Pinus patula* in these mixtures could not be estimated because the quadratic age-per ha C stock relationship gave a negative value.

Table 13: Distribution of C stocks of mixed culture forest plantations involving *Eucalyptus grandis* in different divisions and their productivities

Species composition and division	C stock of spp. 1 ($t\ ha^{-1}$)	C stock of spp. 2 ($t\ ha^{-1}$)	Planted area (ha)	Total C stock of spp. 1 (t)	% of total C stock from spp. 1	Total C stock of spp. 2 (t)	% of total C stock from spp. 2	Total C stock of mixture (t)	% of total mixed C stock
Badulla:									
E. grandis & *E. citriodora*	26.83	30.60	32.70	877.22	46.72	1000.58	53.28	1877.79	0.60
E. grandis & *E. robusta*	72.78	72.78	27.20	1979.51	50.00	1979.51	50.00	3959.02	1.26
E. grandis & *E. globulus*	28.25	33.67	5.50	155.37	45.63	185.16	54.37	340.53	0.11
E. grandis & *E. camaldulensis*	40.72	22.87	95.00	3867.97	64.03	2172.71	35.97	6040.67	1.93
E. grandis & *E. microcorys*	66.94	37.20	350.40	23456.10	64.28	13036.25	35.72	36492.34	11.65
E. grandis & *Eucalyptus* mixed	74.11	31.88	45.30	3357.07	69.92	1444.07	30.08	4801.14	1.53
E. grandis & *Acacia mangium*	39.72	63.78	86.00	3416.21	38.38	5485.24	61.62	8901.44	2.84
E. grandis & *Pinus caribaea*	36.17	41.39	199.20	7205.59	46.63	8245.73	53.37	15451.32	4.93
Mean	**48.19**	**41.77**	**Sub-total**	**44315.02**	**56.91**		**Sub-total**	**77864.26**	**24.87**
Nuwara Eliya:									
E. grandis & *E. robusta*	65.31	65.31	858.40	56061.38	50.00	56061.38	50.00	112122.8	35.81
E. grandis & *E. globulus*	109.30	100.93	46.60	5093.43	51.99	4703.50	48.01	9796.94	3.13
E. grandis & *E. microcorys*	118.65	83.89	239.80	28451.74	58.58	20115.62	41.42	48567.37	15.51
E. grandis & *Eucalyptus* mixed	112.20	103.99	29.00	3253.77	51.90	3015.66	48.10	6269.43	2.00
E. grandis & *Acacia mangium*	75.22	60.82	17.80	1338.87	55.29	1082.57	44.71	2421.44	0.77
E. grandis & *Acacia decurrens*	79.76	118.77	159.60	12729.69	40.18	18954.94	59.82	31684.63	10.12
E. grandis & *Cupressus* sp.	122.88	1.61	9.00	1105.90	98.71	14.45	1.29	1120.35	0.36
E. grandis & *Pinus caribaea*	31.88	36.28	153.90	4906.00	46.77	5583.04	53.23	10489.04	3.35
E. grandis & *Pinus patula*	66.76	22.27	114.50	7643.81	74.99	2549.93	25.01	10193.74	3.26
E. grandis & *Pinus* mixed	109.48	85.46	13.30	1456.14	56.16	1136.68	43.84	2592.81	0.83
Mean	**89.14**	**67.93**	**Sub-total**	**122040.7**	**51.88**		**Sub-total**	**235258.5**	**75.13**
							Total	**313122.8**	

Table 14: Distribution of C stocks of mixed culture forest plantations involving *Eucalyptus camaldulensis* and *Tectona grandis* in different divisions and their productivities

Species composition	Division	C stock of spp. 1 (t ha^{-1})	C stock of spp. 2 (t ha^{-1})	Planted area (ha)	Total C stock of spp. 1 (t)	% of total C stock from spp. 1	Total C stock of spp. 2 (t)	% of total C stock from spp. 2	Total C stock of mixture (t)	% of total mixed C stock†	% of total mixed C stock‡
E. camaldulensis & *E. tereticornis*	Badulla	23.84	43.84	337.0	8032.94	35.22	14772.51	64.78	22805.44	40.76	
E. camaldulensis & *E. torelliana*	Ratnapura	4.83	39.03	3.0	14.49	11.01	117.09	88.99	131.58	0.24	
E. camaldulensis & *A. mangium*	Ratnapura	5.37	86.60	37.0	198.51	5.83	3204.21	94.17	3402.72	6.08	
E. camaldulensis & *A. mangium*	Hambantota	5.90	28.77	33.5	197.66	17.02	963.79	82.98	1161.45	2.08	
E. camaldulensis & *A. mangium*	Matale	16.53	27.15	25.0	413.16	37.84	678.81	62.16	1091.97	1.95	
E. camaldulensis & *A. auriculiformis*	Anuradhapura	5.35	46.39	66.0	353.24	10.34	3062.00	89.66	3415.24	6.10	
E. camaldulensis & *A. auriculiformis*	Ratnapura	6.14	49.58	11.0	67.49	11.01	545.37	88.99	612.86	1.10	
E. camaldulensis & *A. auriculiformis*	Hambantota	5.90	48.61	18.5	109.16	10.82	899.34	89.18	1008.50	1.80	
E. camaldulensis & *Kaya*	Anuradhapura	8.35	59.06	17.0	142.03	12.39	1003.96	87.61	1145.98	2.05	
E. camaldulensis & *P. caribaea*	Matara	7.55	38.25	19.3	145.62	16.48	738.19	83.52	883.81	1.58	
	Mean	**8.97**	**46.73**	**Sub-total**	**9674.30**	**27.13**	**25985.26**	**72.87**	**35659.56**	**63.74**	
E. camaldulensis & *T. grandis*	Ampara	21.02	23.93	107.2	2253.02	46.76	2565.08	53.24	4818.10	8.61	7.89
E. camaldulensis & *T. grandis*	Monaragala	8.26	25.78	129.5	1070.08	24.27	3338.72	75.73	4408.81	7.88	7.22
E. camaldulensis & *T. grandis*	Kurunegala	17.89	27.91	128.8	2304.80	39.07	3594.74	60.93	5899.54	10.54	9.66
E. camaldulensis & *T. grandis*	Puttlam	8.56	8.22	82.6	707.34	51.01	679.30	48.99	1386.64	2.48	2.27
E. camaldulensis & *T. grandis*	Polonnaruwa	21.38	13.63	107.8	2305.03	61.07	1469.14	38.93	3774.17	6.75	6.18
	Mean	**15.42**	**19.89**	**Sub-total**	**8640.27**	**42.59**	**11646.98**	**57.41**	**20287.25**	**36.26**	**33.23**
								Total†	**55946.81**	**100**	
T. grandis & *Eucalyptus* mixed	Ampara	27.53	121.85	39.1	1076.46	18.43	4764.18	81.57	5840.64		9.57
T. grandis & *Eucalyptus mixed*	Kurunegala	26.33	139.94	25.2	663.51	15.84	3526.46	84.16	4189.97		6.86
T. grandis & *Eucalyptus mixed*	Puttlam	7.91	112.13	135.0	1067.95	6.59	15138.07	93.41	16206.02		26.55
T. grandis & *S. macrophylla*	Kurunegala	26.56	59.28	5.2	138.14	30.95	308.25	69.05	446.38		0.73
T. grandis & *A. auriculiformis*	Kurunegala	4.03	18.93	30.3	122.22	17.57	573.53	82.43	695.75		1.14
T. grandis & *A. auriculiformis*	Ratnapura	4.93	41.12	75.5	372.55	10.71	3104.57	89.29	3477.12		5.70
T. grandis & *A. auriculiformis*	Matale	14.62	52.22	52.0	760.26	21.88	2715.23	78.13	3475.50		5.69
T. grandis & *Kaya*	Ampara	5.05	44.27	25.6	129.33	10.24	1133.21	89.76	1262.54		2.07
T. grandis & *Kaya*	Anuradhapura	3.31	15.29	133.3	440.94	17.79	2037.65	82.21	2478.60		4.06
Tectona grandis & *Eucalyptus:Tectona* mixture	Matale	12.40	73.44	31.3	388.16	14.45	2298.73	85.55	2686.89		4.40
	Mean	**13.27**	**67.85**	**Sub-total**	**5159.52**	**12.66**	**35599.88**	**87.34**	**40759.40**		**66.77**
								Total‡	**61046.65**		**100**

† Mixed C stocks involving *Eucalyptus camaldulensis*
‡ Mixed C stocks involving *Tectona grandis*

Table 15: Distribution of C stocks of mixed culture forest plantations involving *Acacia* species in different divisions and their productivities

Species composition	Division	C stock of spp. 1 (t ha^{-1})	C stock of spp. 2 (t ha^{-1})	Planted area (ha)	Total C stock of spp. 1 (t)	% of total C stock from spp. 1	Total C stock of spp. 2 (t)	% of total C stock from spp. 2	Total C stock of mixture (t)	% of total mixed C stock
***Acacia auriculiformis* &:**										
Pinus caribaea	Ratnapura	44.23	35.56	10.3	455.54	55.43	366.26	44.57	821.80	0.56
Pinus caribaea	Kalutara	56.72	42.29	4.0	226.88	57.28	169.18	42.72	396.06	0.27
Tectona grandis	Kurunegala	18.93	4.03	30.3	573.53	82.43	122.22	17.57	695.75	0.47
Tectona grandis	Ratnapura	41.12	4.93	75.5	3104.57	89.29	372.55	10.71	3477.12	2.37
Tectona grandis	Matale	52.22	14.62	52.0	2715.23	78.13	760.26	21.88	3475.50	2.36
E. camaldulensis	Anuradhapura	46.39	5.35	66.0	3062.00	89.66	353.24	10.34	3415.24	2.32
E. camaldulensis	Ratnapura	49.58	6.14	11.0	545.37	88.99	67.49	11.01	612.86	0.42
E. camaldulensis	Hambantota	48.61	5.90	18.5	899.34	89.18	109.16	10.82	1008.50	0.69
	Mean	**44.72**	**14.85**	**Sub-total**	**11582.45**	**83.31**	**2320.36**	**16.69**	**13902.81**	**9.46**
***Acacia mangium* &:**										
E. grandis	Badulla	63.78	39.72	86.0	5485.24	61.62	3416.21	38.38	8901.44	6.05
E. grandis	N'eliya	60.82	75.22	17.8	1082.57	44.71	1338.87	55.29	2421.44	1.65
E. camaldulensis	Ratnapura	86.60	5.37	37.0	3204.21	94.17	198.51	5.83	3402.72	2.31
E. camaldulensis	Hambantota	28.77	5.90	33.5	963.79	82.98	197.66	17.02	1161.45	0.79
E. camaldulensis	Matale	27.15	16.53	25.0	678.81	62.16	413.16	37.84	1091.97	0.74
E. torelliana	Ratnapura	77.89	25.74	54.3	4229.60	75.16	1397.82	24.84	5627.42	3.83
E. torelliana	Kandy	78.91	22.74	33.0	2604.08	77.63	750.42	22.37	3354.50	2.28
E. Eucalyptus mixed	Kurunegala	32.23	101.18	43.2	1392.35	24.16	4371.04	75.84	5763.39	3.92
E. Eucalyptus mixed	Ratnapura	89.32	84.72	12.0	1071.79	51.32	1016.65	48.68	2088.43	1.42
E. Eucalyptus mixed	Kandy	77.02	47.79	36.5	2811.18	61.71	1744.36	38.29	4555.54	3.10
	Mean	**62.25**	**42.49**	**Sub-total**	**23523.60**	**61.31**	**14844.69**	**38.69**	**38368.30**	**26.10**
***Acacia decurrens* &:**										
Pinus caribaea	Nuwara Eliya	82.53	81.51	21.3	1757.83	50.31	1736.15	49.69	3493.98	2.38
Pinus patula	Nuwara Eliya	135.17	0.00	20.5	2771.07	100.00	0.00	0.00	2771.07	1.88
Eucalyptus robusta	Nuwara Eliya	144.01	82.29	5.7	820.87	63.64	469.07	36.36	1289.93	0.88
Eucalyptus globulus	Nuwara Eliya	143.59	103.87	11.5	1651.33	58.03	1194.51	41.97	2845.84	1.94
Eucalyptus grandis	Nuwara Eliya	118.77	79.76	159.6	18954.94	59.82	12729.69	40.18	31684.63	21.55
Eucalyptus mixed	Nuwara Eliya	141.05	138.06	32.9	4640.49	50.54	4542.14	49.46	9182.64	6.25
	Mean	**127.52**	**80.92**	**Sub-total**	**30596.54**	**59.68**	**20671.56**	**40.32**	**51268.09**	**34.87**

- continued

- continued from page 23

Species composition	Division	C stock of spp. 1 (t ha^{-1})	C stock of spp. 2 (t ha^{-1})	Planted area (ha)	Total C stock of spp. 1 (t)	% of total C stock from spp. 1	Total C stock of spp. 2 (t)	% of total C stock from spp. 2	Total C stock of mixture (t)	% of total mixed C stock
***Acacia melanoxylon* &:**										
Cupressus spp.	Nuwara Eliya	74.81	14.35	2.3	172.07	83.91	33.00	16.09	205.07	0.14
				Sub-total	**172.07**	**83.91**	**33.00**	**16.09**	**205.07**	**0.14**
A. mangium & *A. auriculiformis*	Ratnapura	80.70	41.63	54.0	4357.79	65.97	2247.98	34.03	6605.77	4.49
A. mangium & *A. auriculiformis*	Kandy	77.02	38.64	30.0	2310.56	66.59	1159.20	33.41	3469.75	2.36
A. mangium & *A. auriculiformis*	Kalutara	85.32	45.38	194.2	16569.33	65.28	8811.96	34.72	25381.29	17.26
A. mangium & *A. auriculiformis*	Gampaha	53.95	41.62	3.5	188.83	56.45	145.66	43.55	334.49	0.23
	Mean	**74.25**	**41.82**	**Sub-total**	**23426.51**	**65.45**	**12364.79**	**34.55**	**35791.30**	**24.34**
								Total	**139535.60**	**100.00**

† C stock per ha of *Pinus patula* in these mixtures could not be estimated because the age - C stock per ha function used gave a negative value because the higher age of the plantation.

8.2 – 86.6 t ha^{-1}. Accordingly, except in the two divisions mentioned above, the contribution from *E. camaldulensis* to the total C stock of the mixture was lower than that of its associated species. However, the range of productivity of *E. camaldulensis* in the mixed cultures was comparable with that of its monocultures (i.e. 11.8 – 43.0 t ha^{-1} -Table 8), in view of the fact that the mixed cultured contained only 50% of *E. camaldulensis* in their stands.

The specific mixtures that showed the highest productivities for *E. camaldulensis* were those with *E. tereticornis* in Badulla and those with *Tectona grandis* in Ampara and Polonnaruwa. The species, which showed the highest productivities in association with *E. camaldulensis* were *Acacia mangium* in Ratnapura (86.6 t ha^{-1}) and *Kaya* in Anuradhapura (59.1 t ha^{-1}).

Mixed plantations involving *Tectona grandis*: *Tectona grandis*-based mixed plantations contribute nearly 9% to the total C stock from mixed cultures (Table 12). These are also distributed predominantly in the Dry and Intermediate Zones (Table 14). Mixed cultures with *E. camadulensis* in Ampara, Moneragala, Kurunegala, Puttalam and Polonnaruwa contributed 33% to the total C stock in *Tectona grandis*-based mixed plantations while the mixture of *Tectona grandis* and *Eucalyptus* in Puttalam contributed 26.5%. In contrast to the *Eucalyptus* species, the productivity of *Tectona* in mixed cultures (3.3 – 27.9 t ha^{-1} -Table 14) was lower than that of its monocultures (11.9 – 131.7 t ha^{-1} - Table 6) even after allowing for its 50% share in the mixed tree population. This may be an indication that *Tectona* is a species, which prefers monoculture conditions to achieve its maximum productivity. While *Tectona* had slightly greater productivities than *E. camaldulensis* in most of their mixtures, its productivities in mixtures with other species were substantially lower in comparison to the productivity of its associated species (Table 14). For example, *Eucalyptus* in association with *Tectona* in Ampara, Kurunegala and Puttalam achieved productivities ranging from 112 – 140 t ha^{-1} while *Swietenia macrophylla* in association with *Tectona* in Kurunegala achieved a productivity of 60 t ha^{-1}. Accordingly, except in the mixtures with *E. camaldulensis* in Ampara, Moneragala and Kurunegala, the contribution from *Tectona* to the total C stock of mixed plantations was lower than that of its associated species.

Mixed plantations involving *Acacia* species: Mixed plantations involving different *Acacia* species (i.e. *A. auriculiformis*, *A. mangium*, *A. decurrens* and

A. melanoxylon) with other tree species (i.e. *Pinus caribaea*, *P. patula*, *Tectona grandis*, *Eucalyptus camaldulensis*, *E. grandis*, *E. torreliana*, *E. robusta*, *E. globulus* and *Cuprusses* spp.) contribute nearly 22% to the total C stock from mixed plantations while occupying 21% of the planted area (Table 12). Mixtures of *A. mangium* and *A. auriculiformis*, all of which were in the Wet Zone divisions of Ratnapura, Kandy, Kalutara and Gampaha, contributed 24% of the total C stock from *Acacia*-based mixed plantations (Table 15). In all these divisions, *A. mangium* contributed a greater percentage (57-67%) to the total C stock from the mixed plantations. This reflected the greater productivity of *A. mangium* (54 – 85 t ha^{-1}) when compared to *A. auriculiformis* (39 – 45 t ha^{-1}). The productivities in mixed cultures of these two species, at 50% plant densities, are approximately equivalent to their respective productivities in monocultures in these divisions (Tables 10 and 11). Mixtures involving *A. decurrens*, all of which were located in Nuwara Eliya division, had the highest (39%) contribution to the total C stock from *Acacia*-based mixed plantations. In the mixtures of *A. decurrens* with *Pinus caribaea* and mixed *Eucalyptus*, the contribution of *A. decurrens* to the total C stock was around 50%. In the rest of the mixtures, *A. decurrens* had a greater percentage contribution to the total C stock of the mixture. Except in the mixtures with *Pinus caribaea*, *A. decurrens* had a much higher productivity (119 – 144 t ha^{-1} at 50% plant density) (Table 15) than its monocultures (140 t ha^{-1} at 100% plant density) (Table 4). *A. mangium* had mixtures with different *Eucalyptus* species across a range of divisions traversing Wet, Intermediate and Dry Zones. These mixtures contributed 26% to the total C stock from *Acacia*-based mixed plantations. With the exception of the mixture with *E. grandis* in Nuwara Eliya and that with mixed *Eucalyptus* species in Kurunegala, *A. mangium* had the greater percentage contribution (51% – 94%) to total C stock of the mixture. In the divisions of Hambantota, Kurunegala and Matale, which were in the Dry and Intermediate Zones, the productivity of *A. mangium* in mixtures was much lower (27 – 32 t ha^{-1}) than in the rest of the divisions (61 – 89 t ha^{-1}), which were predominantly in the Wet Zone. *A. auriculiformis* had mixtures with three other species (*Pinus caribaea*, *Tectona grandis* and *E. camaldulensis*), which were distributed in a wide range of divisions traversing Wet, Intermediate and Dry Zones. These mixtures contributed 10% to the total C stock from *Acacia*-based mixed plantations. Irrespective of the climatic zone, in all these mixtures, *A. auriculiformis* had a greater percentage contribution (55% - 90%) to the total C stock of the mixture. Except in the mixture with *Tectona grandis* at Kurunegala, the productivity of *A. auriculiformis* in mixtures varied within a narrow range from 44 – 58 t ha^{-1}. This was slightly higher than the monoculture average productivity of 87 t ha^{-1} (at 100% plant density) for *A. auriculiformis* (Table 4).

Combined per ha C stocks of mixed forest plantations

Mixed plantations involving *Acacia decurrens* and different species of *Eucalyptus* grown in Nuwara Eliya showed the highest combined per ha C stocks (Tables 12 and 15), with the mixture between *A. decurrens* and *Eucalyptus* mixed achieving 279 t ha^{-1}. This was followed by *A. decurrens* & *E. globulus* (247 t ha^{-1}), and *A. decurrens* & *E. robusta* (226 t ha^{-1}). Three mixtures involving *E. grandis* with other *Eucalyptus* species, also growing in Nuwara Eliya, had combined per ha C stocks above 200 t ha^{-1} (Tables 12 and 13). In addition, mixtures of *A. decurrens* & *E. grandis* (199 t ha^{-1}) and *E. grandis* & *Pinus* mixed (195 t ha^{-1}) in Nuwara Eliya had combined per ha C productivities nearing 200 t ha^{-1}.

None of the mixed plantations in any other division (Tables 13 – 15) reached combined per ha C stocks of those mentioned above in Nuwara Eliya. In Badulla, which had the second highest area of mixed plantations behind Nuwara Eliya, the highest combined per ha C stock was in the *E. grandis* & *E. robusta* mixture with 146 t ha^{-1} (Table 13). Mixtures of *Tectona grandis* and different *Eucalyptus* species were the ones, which had the highest combined per ha C stocks in those located in the Intermediate and Dry Zones (Table 14), with 166, 149 and 120 t ha^{-1} in *Tectona* & *Eucalyptus* mixed plantations in Kurunegala, Ampara and Puttalam respectively. In addition, the mixture of *Acacia mangium* and *Eucalyptus* mixed in Kurunegala also had 133 t C ha^{-1} combined (Table 15).

Among species mixtures in the Wet Zone, those with *A. mangium* had the highest per ha combined C stocks (Table 15) with the mixture of *Acacia mangium* and *Eucalyptus* mixed in Ratnapura having 174 t C ha^{-1}. This is followed by mixtures of *A. mangium* and *A. auriculiformis* in Kalutara, Ratnapura and Kandy with 131, 122 and 116 t C ha^{-1}, respectively.

Distribution of monoculture C stocks by divisions

Table 16 shows the distribution of monoculture C stocks in the different divisions. It shows that nearly 58% of the monoculture C stocks are located in four divisions, namely, Badulla (17.71%), Nuwara Eliya (16.57%), Kurunegala (12.42%) and Kandy (10.92%). Nuwara Eliya and Badulla showed the highest average productivities with 124 and 156 t ha^{-1}, respectively. Productivities of the divisions located in the Dry and drier Intermediate Zones (i.e. Kurunegala) were clearly lower (25 – 69 t ha^{-1}) than those in the Wet and wetter Intermediate Zones (i.e. Badulla) (60 – 154 t ha^{-1}). Because of the lower productivity in the Dry Zone, primarily because of the lower water availability, a division such as Puttalam contributed only 4.4% to the total monoculture C stock despite having 13% of the monoculture plantation area. In contrast, because of the higher productivity of the Wet Zone, Nuwara Eliya had 16.6% of the monoculture C stock while having only 7.9% of the total monoculture plantation area.

In Badulla, *Pinus caribaea* provides the largest contribution (66%) to the total C stock (Table 17) because of its substantially higher productivity (205 t ha^{-1}) in this environment and also because of higher percentage of area planted with it (41%). *E. grandis* (13%) and *E. camaldulensis* (7%) are the other two species which provided major contributions to the total C stock in Badulla, with the former having nearly twice the productivity of the latter. It can be noted that the Badulla division contains a wide range of plantation forest species with several of them having high levels of productivity in this environment (i.e. *P. oocarpa*, *P. patula*, *E. microcorys*, *E. torreliana* and *Acacia melanoxylon*). In Nuwara Eliya, the total monoculture C stock is dominated by *E. grandis* (47%) and *P. caribaea* (36%), followed by *E. robusta* (12%). All three of the above species have high productivities ranging from 157 to 168 t ha^{-1}, indicating their suitability for the environmental conditions in Nuwara Eliya. In addition, *E. pilularis* and *E. microcorys* showed high productivities.

Pinus caribaea dominated the total monoculture C stocks of most divisions in the Wet and wetter Intermediate Zones, with 97% in Matara, 95% in Kandy, 87% in Kalutara, 61% in Matale and 73% in Ratnapura. However, the respective productivities of *P. caribaea* in these divisions were lower than those of Badulla and Nuwara Eliya. Among the above mentioned divisions, *P. caribaea* in the mid-elevations (i.e. Kandy, Matale and Kegalle) had higher productivities than those in the lower elevations (i.e. Matara, Ratnapura, Gampaha and Kalutara).

Table 16: Distribution of monoculture C stocks according to divisions

Division	Total C stock (t)	% of total C stock	Total area (ha)	% of total area	Average productivity (t ha^{-1})
Ampara	34990.38	0.83	772.2	1.34	45.31
Anuradhapura	124989.34	2.96	4547.7	7.89	27.48
Badulla	748261.64	17.71	5943.3	10.31	125.90
Galle	39699.67	0.94	658.6	1.14	60.28
Gampaha	45275.83	1.07	410.5	0.71	110.29
Hambantota	131809.03	3.12	3062.4	5.31	43.04
Jaffna	15836.75	0.37	230.6	0.40	68.68
Kalutara	102244.65	2.42	1130.9	1.96	90.41
Kandy	461308.01	10.92	3537.4	6.14	130.41
Kegalle	45633.49	1.08	405.1	0.70	112.65
Kurunegala	525018.47	12.42	8016.8	13.91	65.49
Matale	303938.85	7.19	3867.2	6.71	78.59
Matara	138177.70	3.27	1530.8	2.66	90.27
Monaragala	205087.83	4.85	4210.0	7.31	48.71
Nuwara Eliya	700076.12	16.57	4535.3	7.87	154.36
Polonnaruwa	145752.66	3.45	3763.1	6.53	38.73
Puttlam	186554.51	4.41	7596.4	13.18	24.56
Ratnapura	270936.13	6.41	3400.5	5.90	79.68
Total	**4225591.07**	**100.00**	**57618.8**	**100.00**	

Table 17: Species composition of monoculture C stocks of different divisions

Division	Species	C stock per ha (t ha^{-1})	Planted area (ha)	% of planted area in each division	Total C stock of the division (t)	% of total C stock of each division
Ampara	*Tectona grandis*	46.24	615.0	79.6	28439.29	81.28
Ampara	*E. camaldulensis*	41.67	157.2	20.4	6551.09	18.72
	Divisional total		**772.2**		**34990.38**	
Anuradhapura	*Tectona grandis*	27.15	3443.9	75.7	93484.99	74.79
Anuradhapura	*Swietenia macrophylla*	87.12	6.0	0.1	522.73	0.42
Anuradhapura	*Eucalyptus grandis*	72.97	9.6	0.2	700.53	0.56
Anuradhapura	*E. camaldulensis*	12.73	860.0	18.9	10944.27	8.76
Anuradhapura	*Acacia mangium*	52.84	41.2	0.9	2176.94	1.74
Anuradhapura	*Acacia auriculiformis*	91.76	187.0	4.1	17159.87	13.73
	Divisional total		**4547.7**		**124989.34**	
Badulla	*Tectona grandis*	11.85	20.8	0.3	246.56	0.03
Badulla	*Eucalyptus cloeziana*	70.57	5.8	0.1	409.31	0.05
Badulla	*Eucalyptus robusta*	71.93	47.7	0.8	3431.12	0.46
Badulla	*Eucalyptus citriodora*	86.81	7.5	0.1	651.07	0.09
Badulla	*Eucalyptus globulus*	63.85	3.8	0.1	242.62	0.03
Badulla	*Eucalyptus grandis*	83.22	1207.2	20.3	100463.85	13.43
Badulla	*E. camaldulensis*	43.04	1219.7	20.5	52500.54	7.02
Badulla	*Eucalyptus tereticornis*	86.16	646.1	10.9	55669.60	7.44
Badulla	*Eucalyptus microcorys*	114.10	152.3	2.6	17377.24	2.32
Badulla	*Eucalyptus torelliana*	111.10	15.6	0.3	1733.20	0.23
Badulla	*Acacia mangium*	74.41	114.8	1.9	8542.09	1.14
Badulla	*Acacia melanoxylon*	111.89	1.0	0.0	111.89	0.01
Badulla	*Cupressus* sp.	23.56	4.0	0.1	94.25	0.01
Badulla	*Pinus caribaea*	204.79	2413.3	40.6	494208.94	66.05
Badulla	*Pinus patula*	146.31	76.2	1.3	11149.07	1.49
Badulla	*Pinus oocarpa*	190.71	7.5	0.1	1430.30	0.19
	Divisional total		**5943.3**		**748261.64**	
Galle	*E. camaldulensis*	11.81	2.5	0.4	29.52	0.07
Galle	*Pinus caribaea*	60.46	656.1	99.6	39670.16	99.93
	Divisional total		**658.6**		**39699.67**	
Gampaha	*Tectona grandis*	131.72	160.4	39.1	21127.68	46.66
Gampaha	*Swietenia macrophylla*	105.27	74.7	18.2	7863.58	17.37
Gampaha	*E. camaldulensis*	14.73	10.5	2.6	154.67	0.34
Gampaha	*Acacia mangium*	162.62	27.6	6.7	4488.35	9.91
Gampaha	*Acacia auriculiformis*	87.64	68.9	16.8	6038.71	13.34
Gampaha	*Pinus caribaea*	81.91	68.4	16.7	5602.84	12.37
	Divisional total		**410.5**		**45275.83**	
Hambantota	*Tectona grandis*	82.37	850.5	27.8	70058.39	53.15
Hambantota	*Swietenia macrophylla*	101.83	10.7	0.3	1089.63	0.83
Hambantota	*Eucalyptus grandis*	175.72	1.5	0.0	263.58	0.20
Hambantota	*E. camaldulensis*	14.85	1908.2	62.3	28337.02	21.50
Hambantota	*Acacia auriculiformis*	85.92	28.1	0.9	2414.48	1.83
Hambantota	*Casuarina*	42.90	27.0	0.9	1158.17	0.88
Hambantota	*Pinus caribaea*	120.51	236.4	7.7	28487.76	21.61
	Divisional total		**3062.4**		**131809.03**	
Jaffna	*Eucalyptus grandis*	104.83	41.7	18.1	4371.25	27.60

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continued from page 30 –

Division	Species	C stock per ha (t ha^{-1})	Planted area (ha)	% of planted area in each division	Total C stock of the division (t)	% of total C stock of each division
Jaffna	*Casuarina*	60.70	188.9	81.9	11465.50	72.40
	Divisional total		**230.6**		**15836.75**	
Kalutara	*Swietenia macrophylla*	106.49	0.7	0.1	74.55	0.07
Kalutara	*Eucalyptus deglupta*	134.33	1.0	0.1	134.33	0.13
Kalutara	*Acacia mangium*	161.53	76.7	6.8	12389.02	12.12
Kalutara	*Acacia auriculiformis*	88.45	10.0	0.9	884.47	0.87
Kalutara	*Pinus caribaea*	85.14	1042.5	92.2	88762.29	86.81
	Divisional total		**1130.9**		**102244.65**	
Kandy	*Tectona grandis*	32.15	51.2	1.4	1645.97	0.36
Kandy	*Eucalyptus robusta*	63.98	6.5	0.2	415.87	0.09
Kandy	*Eucalyptus grandis*	187.94	2.0	0.1	375.88	0.08
Kandy	*E. camaldulensis*	40.62	7.6	0.2	308.70	0.07
Kandy	*Eucalyptus torelliana*	74.67	4.0	0.1	298.68	0.06
Kandy	*Acacia mangium*	166.32	93.2	2.6	15500.64	3.36
Kandy	*Acacia auriculiformis*	90.73	20.0	0.6	1814.51	0.39
Kandy	*Acacia decurrens*	140.33	7.5	0.2	1052.48	0.23
Kandy	*Pinus caribaea*	131.49	3345.4	94.6	439895.29	95.36
	Divisional total		**3537.4**		**461308.01**	
Kegalle	*Swietenia macrophylla*	97.91	63.3	15.6	6197.97	13.58
Kegalle	*Acacia mangium*	154.29	120.1	29.6	18530.37	40.61
Kegalle	*Acacia auriculiformis*	85.68	148.5	36.7	12722.86	27.88
Kegalle	*Pinus caribaea*	111.78	73.2	18.1	8182.30	17.93
	Divisional total		**405.1**		**45633.49**	
Kurunegala	*Tectona grandis*	54.36	4117.1	51.4	223813.39	42.63
Kurunegala	*Swietenia macrophylla*	97.85	2373.7	29.6	232268.04	44.24
Kurunegala	*Eucalyptus grandis*	91.07	83.2	1.0	7576.80	1.44
Kurunegala	*E. camaldulensis*	38.46	1277.2	15.9	49119.68	9.36
Kurunegala	*Acacia mangium*	54.88	60.6	0.8	3325.59	0.63
Kurunegala	*Acacia auriculiformis*	90.45	89.4	1.1	8085.88	1.54
Kurunegala	*Casuarina*	53.15	15.6	0.2	829.09	0.16
	Divisional total		**8016.8**		**525018.47**	
Matale	*Tectona grandis*	35.52	1509.2	39.0	53611.75	17.64
Matale	*E. camaldulensis*	42.72	697.8	18.0	29807.16	9.81
Matale	*Acacia mangium*	54.32	44.5	1.2	2417.39	0.80
Matale	*Acacia auriculiformis*	88.96	367.1	9.5	32657.07	10.74
Matale	*Pinus caribaea*	148.52	1248.6	32.3	185445.49	61.01
	Divisional total		**3867.2**		**303938.85**	
Matara	*Eucalyptus grandis*	139.81	19.3	1.3	2698.30	1.95
Matara	*E. camaldulensis*	15.13	14.4	0.9	217.87	0.16
Matara	*Eucalyptus torelliana*	78.08	20.0	1.3	1561.52	1.13
Matara	*Pinus caribaea*	90.52	1477.1	96.5	133700.01	96.76
	Divisional total		**1530.8**		**138177.70**	
Monaragala	*Tectona grandis*	53.81	3426.0	81.4	184337.93	89.88
Monaragala	*Eucalyptus grandis*	82.38	138.5	3.3	11409.97	5.56
Monaragala	*E. camaldulensis*	14.41	643.5	15.3	9276.03	4.52
Monaragala	*Pinus caribaea*	31.95	2.0	0.0	63.89	0.03
	Divisional total		**4210.0**		**205087.83**	

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continued from page 31 –

Division	Species	C stock per ha (t ha^{-1})	Planted area (ha)	% of planted area in each division	Total C stock of the division (t)	% of total C stock of each division
Nuwara Eliya	*Eucalyptus pilularis*	182.27	9.0	0.2	1640.46	0.23
Nuwara Eliya	*Eucalyptus robusta*	157.36	517.5	11.4	81433.81	11.63
Nuwara Eliya	*Eucalyptus grandis*	168.46	1962.7	43.3	330640.11	47.23
Nuwara Eliya	*Eucalyptus microcorys*	121.82	55.2	1.2	6724.25	0.96
Nuwara Eliya	*Cupressus* sp.	28.12	20.5	0.5	576.45	0.08
Nuwara Eliya	*Pinus caribaea*	164.01	1528.7	33.7	250725.97	35.81
Nuwara Eliya	*Pinus patula*	64.15	441.7	9.7	28335.07	4.05
	Divisional total		**4535.3**		**700076.12**	
Polonnaruwa	*Tectona grandis*	32.68	1704.6	45.3	55702.28	38.22
Polonnaruwa	*E. camaldulensis*	42.47	2006.5	53.3	85210.48	58.46
Polonnaruwa	*Acacia auriculiformis*	93.08	52.0	1.4	4839.90	3.32
	Divisional total		**3763.1**		**145752.66**	
Puttlam	*Tectona grandis*	31.30	3939.8	51.9	123334.80	66.11
Puttlam	*Swietenia macrophylla*	82.67	40.8	0.5	3372.82	1.81
Puttlam	*E. camaldulensis*	13.36	3209.6	42.3	42871.67	22.98
Puttlam	*Eucalyptus tereticornis*	16.38	224.1	3.0	3670.87	1.97
Puttlam	*Acacia mangium*	52.54	85.0	1.1	4465.61	2.39
Puttlam	*Acacia auriculiformis*	91.03	97.1	1.3	8838.74	4.74
	Divisional total		**7596.4**		**186554.51**	
Ratnapura	*Tectona grandis*	23.14	448.4	13.2	10375.44	3.83
Ratnapura	*Swietenia macrophylla*	92.14	111.0	3.3	10227.66	3.77
Ratnapura	*Eucalyptus robusta*	62.88	5.7	0.2	358.43	0.13
Ratnapura	*Eucalyptus grandis*	196.95	22.8	0.7	4490.36	1.66
Ratnapura	*Eucalyptus tereticornis*	48.17	8.0	0.2	385.35	0.14
Ratnapura	*Eucalyptus torelliana*	64.17	30.0	0.9	1925.17	0.71
Ratnapura	*Acacia mangium*	119.56	181.8	5.3	21735.91	8.02
Ratnapura	*Acacia auriculiformis*	79.39	307.3	9.0	24397.91	9.01
Ratnapura	*Pinus caribaea*	86.21	2285.5	67.2	197039.90	72.73
	Divisional total		**3400.5**		**270936.13**	
	Grand total		**57618.8**		**4225591.07**	

DISCUSSION

The present study showed that Sri Lanka had a considerable amount of sequestered carbon in its plantation forests, which amounted to 4.91 million tons in 2008. The total area of forest plantations accounted for in this study (i.e. 63568.4 ha) covered approximately 1% of the total land area of Sri Lanka. In order to place the present C stocks of Sri Lankan forest plantations within the context of C stocks elsewhere in the world, our calculations of per ha C stocks were compared with the spatially averaged values published by the IPCC (2006) for different ecological zones (termed as 'biome default values') and with averaged published site data from a recent comprehensive study (Keith *et al.*, 2009). In addition to the respective biome defaults, which take into account both natural forests and plantations, IPCC also gives specific estimates for average above-ground biomass of forest plantations in different ecological zones (Table 4.12 in IPCC, 2006). These were originally given in IPCC's 'Good Practice Guidance for Land Use, Land Use Change and Forestry' (2003) and are also used as benchmarks for comparison of C stocks of Sri Lankan forest plantations calculated in the present study.

Comparison of monoculture C stocks with benchmark average values

Badulla and Nuwara Eliya, which are the two divisions containing the highest percentages of monoculture C stocks (Table 16) can be categorized as 'Tropical Moist' (i.e. mean annual temperature > 18 ^{o}C; mean annual precipitation 1000 – 2000 mm with a mostly wet climate including 3 – 5 relatively dry months) and 'Tropical Montane' (i.e. mean annual temperature > 18 ^{o}C; altitude > 1000 m above sea level), respectively (IPCC, 2006). The mean annual precipitation (MAP) and temperature of Badulla (altitude 670 m) were 1764 ± 49.5 mm and 23.506 ± 0.049 ^{o}C during the period from 1950 –1989 and 1702 ± 68.6 mm and 24.294 ± 0.079 ^{o}C during 1990 – 2007 (De Costa, 2008). The corresponding data for Nuwara Eliya (altitude 1895 m) are 2001 ± 55.2 mm and 15.802 ± 0.052 ^{o}C (1950-1989) and 1864 ± 73.5 mm and 16.175 ± 0.054 ^{o}C (1990-2007). Therefore, it can be seen that climatic criteria for classification of Badulla were clearly within those specified for Tropical Moist climatic region (Climate Code TAWa according to IPCC, 2006). However, those of Nuwara Eliya did not exactly fall within the criteria specified for the Tropical Montane Climatic region (Code TM), because the mean annual temperatures are lower than 18 ^{o}C.

Monoculture plantations of *Pinus caribaea*, which is the main plantation forest species contributing 44 % to the total monoculture C stocks (Table 4), had substantially greater C stocks in Badulla (205 t ha^{-1}) and Nuwara Eliya (164 t ha^{-1}) in comparison to the spatially averaged biome default (SABD) values of 142 t ha^{-1} for TAWa and 112 t ha^{-1} for TM climates. The site specific average C stocks from Keith *et al.* (2009) for TM (i.e. 167 ± 17 t ha^{-1}, no. of sites, n =3) is on par with our value of 164 t ha^{-1} for *P. caribaea* at Nuwara Eliya. However, Keith *et al.* (2009)'s value of 248 ± 100 t ha^{-1} (n=5) is higher than the value of 205 t ha^{-1} for *P. caribaea* at Badulla. Yet, it should be noted that Keith *et al.* (2009)'s values include the dead biomass carbon as well, whereas our values include only the carbon in living biomass. The corresponding site-specific average above-ground living biomass values of Keith *et al.* (2009) are 179 ± 96 t ha^{-1} (n=14) for TAWa and 127 ± 8 t ha^{-1} (n=3) for TM. These are very close to our above-ground C stock values for *P. caribaea* of 157 t ha^{-1} for Badulla and 126 t ha^{-1} for Nuwara Eliya. Similarly, our C stock estimates for *Eucalyptus grandis* in Nuwara Eliya (i.e. 168 and 129 t ha^{-1} for total and above-ground C stocks, Table 7) are also on par with Keith *et al.* (2009)'s values while being substantially higher than IPCC (2006)'s SABD for TM of 112 t ha^{-1}. However, C stocks of *E. grandis* in Badulla (83 and 64 t ha^{-1} for total and above-ground C stocks) are lower than the corresponding SABD for TAWa (142 t ha^{-1}). On the other hand, the above mentioned above-ground C stocks of *P. caribaea* and *E. grandis* in Badulla and Nuwara Eliya are substantially higher than the average values specified by IPCC (2003) for forest plantations in the Tropical Moist (60 t ha^{-1}) and Tropical Montane (45 t ha^{-1}) climatic zones.

None of the monoculture forest plantations in the low- and mid-country (altitude < 1000 m above sea level) Wet Zone of Sri Lanka have per ha C stocks, which are on par with the IPCC (2006)'s SABD value of 213 t ha^{-1} or the site-specific average value of 231 ± 75 (n=7) of Keith *et al.* (2009) for the 'Tropical Wet' (i.e. mean annual temperature > 18 oC; MAP > 2000 mm with less than 3 relatively dry months) climate region (Climate Code TAr according to IPCC, 2006). Among the monoculture plantations which had the highest C stocks in this region were *Eucalyptus grandis* in Ratnapura (197 t ha^{-1}) and Kandy (188 t ha^{-1}) (Table 7) and *Acacia mangium* in Gampaha, Kalutara and Kandy (162 – 166 t ha^{-1}) (Table 10). However, it should be noted that calculations of the present study include only the C stocks in live standing biomass, whereas the two standards against which these are compared take into account the dead biomass as well. Furthermore, the C stock values of the two standards are for all forest types, including both natural forests and plantations, in the respective climate regions. Therefore, if adjusted to take into account the above differences, the C stocks in forest plantations of *Eucalyptus grandis* and *Acacia mangium* in the above-mentioned divisions may be closer to the respective standards in this climate region. When compared with the IPCC (2006) estimates of above-ground C stocks for forest plantations in the 'Tropical Wet' zone (75 t ha^{-1}), the above-ground C stocks of *E. grandis* in Ratnapura (151 t ha^{-1}) and *Acacia mangium* in Gampaha, Kalutara and Kandy (124 – 127 t ha^{-1}) are much higher. Nevertheless, it is possible that the C stocks of the majority of forest plantations in the lower elevations of the Wet Zone are below the average potential of this climate zone. This may indicate either inferior forest management or inferior site quality such as lower soil fertility in the sites where Wet Zone plantations have been established. The latter is the more likely reason as most of the forest plantations in the Wet Zone have been established in degraded soils in sloping lands as a means of arresting their continued degradation (Pushparajah, 1987; Sahajananthan, 1987).

Major tree species in the forest plantations in the Dry Zone of Sri Lanka are *Tectona grandis*, *Eucalyptus camaldulensis*, *Swietenia macrophylla* and *Acacia auriculiformis*. Out of these, the calculated maximum C stocks of *Tectona grandis* (82 t ha^{-1} in Hambantota –Table 6), *Swietenia macrophylla* (98 t ha^{-1} in Kurunegala –Table 9) and *Acacia auriculiformis* (90 – 93 t ha^{-1} in Polonnaruwa, Kurunegala, Anuradhapura and Puttalam –Table 11) come closer to the standards for the 'Tropical Dry' (i.e. mean annual temperature > 18 ^{o}C; MAP < 1000 mm with 5-8 relatively dry months) climate region (Climate Code TAWb according to IPCC). The relevant standards for TAWb are 105 t ha^{-1} (IPCC, 2006) and 111 t ha^{-1} (n=1) (Keith *et al.*, 2009). It is notable that *Tectona grandis* and *Acacia auriculiformis* achieved their maximum per ha C stocks in the Wet Zone divisions with 132 t ha^{-1} for *T. grandis* in Gampaha (Table 6) and 154 t ha^{-1} for *A. auriculiformis* in Kegalle (Table 11). The maximum per ha C stocks of *E. camaldulensis* (43 t ha^{-1} in Badulla and Matale and 42 t ha^{-1} in Polonnaruwa and Ampara –Table 8), which occupies 21 % of the monoculture plantation area (Table 4) and which is distributed predominantly in the Dry Zone divisions (i.e. 73 % of its planted area –Table 8), are much lower than the standards of Keith *et al*. (2009) and IPCC (2006). However, the maximum above-ground C stocks of all four major Dry Zone plantation forest species (i.e. 63, 75, 70 and 33 t ha^{-1} for *Tectona*, *Swietenia*, *A. auriculiformis* and *E. camaldulensis*) are higher than or on par with IPCC (2003)'s estimate of average above-ground C stocks of plantation forests in the 'Tropical Dry' climate zone (30 t ha^{-1}). Yet, in some of the divisions, which contain substantial areas of *Tectona* (21 and 24 t ha^{-1} in Anuradhapura and Puttalam, which respectively had 17 % and 24 % of the planted area) and *E. camaldulensis* (10 and 11 t ha^{-1} in Puttalam and Hambantota having 27 % and 16 % of the planted area), the above-ground per ha C stocks were below the IPCC average. On the other hand, the above-ground per ha C stocks of all divisions planted with *Swietenia* (63 – 82 t ha^{-1}) and *A. auriculiformis* (61 – 71 t ha^{-1}) were substantially above the relevant IPCC (2006) value of 30 t ha^{-1}.

Comparison of mixed culture C stocks with benchmark average values

Our calculations have shown that the mixed culture forest plantations have, on average, greater per ha C stocks (114.54 t ha^{-1} -Table 12) than the monocultures (73.34 t ha^{-1} -Table 4). It is notable that except the mixed cultures involving *Tectona grandis* and *Eucalyptus camaldulensis*, most of the mixed culture plantations are located in the Wet Zone (Tables 13-15). In addition to the possible synergistic effects of mixed cultures (Piotto *et al.*, 2003; Piotto *et al.*, 2004), the greater overall productivity of mixed cultures could be due to the more favourable environmental conditions found in the Wet Zone for tree growth and carbon sequestration. Remarkably, combined per ha C stocks exceeding 190 t ha^{-1} in the mixed plantations involving *Acacia decurrens* with three *Eucalyptus* species (i.e. *E. globulus*, *E. robusta* and *E. grandis*) and with *Eucalyptus* mixed and with *Pinus* mixed (Tables 12, 13 and 15) grown in Nuwara Eliya exceeded by a substantial margin the respective benchmark values for the 'Tropical Montane' climate zone, i.e. 167 t ha^{-1} (Keith *et al.*, 2009), 112 t ha^{-1} (IPCC, 2006) and 45 t ha^{-1} (IPCC, 2003). This indicates a combination of environmental conditions (i.e. precipitation, temperature and soil fertility), which are highly conducive to fast growth of these tree species. It was mentioned earlier that the annual mean temperature of Nuwara Eliya (i.e. ~ 16 ^{o}C) is below the threshold of 18 oC to be included in the 'Tropical Montane' climate region. The site-specific C sequestration data of Keith *et al.* (2009) show that in a precipitation regime of around 2000 mm yr^{-1}, total per ha C stocks increase as annual mean temperatures decrease from around 28 down to 10 ^{o}C (Figure 3 of Keith *et al.*, 2009). This is primarily because of the lower respiration rates at lower temperatures (Woodward *et al.*, 1995). Hence, it is highly likely that, the combination of higher precipitation, which promotes greater photosynthesis, and lower temperature, which reduces respiration, are responsible for the exceptionally high carbon sequestration rates of the mixed forest plantations in Nuwara Eliya.

In Badulla, the maximum combined per ha C stock of 146 t ha^{-1} in the mixture between *E. grandis* & *E. robusta* was on par with the SABD of 142 t ha^{-1} for Tropical Moist climate region (IPCC, 2006). However, it was much lower than the site specific average of 248 t ha^{-1} as estimated by Keith *et al.* (2009) for the same climate zone. On the other hand, the maximum combined per ha C stocks of mixtures between *Tectona grandis* and different *Eucalyptus* species and those between *Acacia mangium* and *Eucalyptus* mixed in Kurunegala in the Intermediate and Dry Zones (120 – 166 t ha^{-1}) exceeded all benchmark average C stock values for the 'Tropical Dry' climate region, i.e. 30, 105 and 111 t ha^{-1} for IPCC (2003), IPCC (2006) and Keith *et al.* (2009). However, in the Wet Zone, the maximum combined per ha C stock of 174 t ha^{-1} for the mixture of *Acacia mangium* and *Eucalyptus* mixed in Ratnapura was below the benchmark averages for the 'Tropical Wet' climate zone, i.e. 231 and 213 t ha^{-1} for Keith *et al*. (2009) and IPCC (2006). However, it can be noted that Keith *et al.* (2009) 's site-specific average value, which is based on data from seven sites within this climate zone, has a standard deviation of 75 t ha^{-1}, which brings the maximum value of our study also into the confidence interval of Keith *et al.* (2009)'s estimate. Examination of Keith *et al.* (2009)'s plot (i.e. Figure 3) of per ha C stocks of individual sites having rainfall and annual mean temperature regimes comparable to those of Ratnapura, i.e. 3700 mm yr^{-1} and 27.4 ^{o}C, respectively (De Costa, 2008), show that several sites have per ha C stocks which are comparable to the 174 t ha^{-1} observed in our study. Although the higher rainfall regime of this climate zone favoured higher photosynthetic rates, the higher temperatures probably increased the respiration rates so that the C sequestration rates did not increase up to the levels achieved under the cooler temperatures in Nuwara Eliya. This is supported by the findings of Clark *et al.* (2003), who showed a significant negative correlation between annual growth rates of six tropical tree species in a tropical rainforest in Costa Rice and annual mean of daily minimum temperature. This was attributed to the increased tree respiration rates at higher temperatures as respiration rate increases exponentially with increasing temperature while the photosynthetic rate increases only up to an optimum and then decreases (Fitter & Hay, 1981; Saxe *et al.*, 2001). This has important implications for all forests in the tropics, both natural forests and plantations, where the productivity is likely to decrease with future global warming (Grace & Rayment, 2000; Valentini *et al.*, 2000; Lewis, 2006).

Distribution of C stocks in forest plantations of different age classes

Carbon stocks of forest plantations obviously vary with their age. Biomass accumulation would be slow in the young plantations until they establish their canopy cover to maximize radiation interception and photosynthesis. This was reflected in the age-wise distribution of monoculture C stocks of the present study also (Figure 1), with less than 1% of the total monoculture C stocks being present in forest plantations younger than 10 years. However, when individual species were considered, *Eucalyptus grandis* (Figure 2c) and *Acacia auriculiformis* (Figure 2g) had around 5% of their C stocks in plantations younger than 10 years while *Tectona grandis* (Figure 2b) had less than 1%. This reflected the higher early growth rates of the *Eucalyptus* and *Acacia* species growing in the areas with more favourable climates for forest growth (i.e. Wet and Intermediate Zones) (Tables 7 and 11) as compared to the lower early growth rates of *Tectona*, which was growing predominantly in the less favourable Dry Zone districts (Table 6).

After achieving a considerable canopy cover, biomass accumulation and carbon sequestration of a forest plantation reaches an exponential phase at an age, which is determined by the inherent growth rates of the plant species and the environmental conditions under which the species is growing. This exponential phase of forest growth and carbon accumulation would later shift to a linear phase. Carbon stocks of forest plantations are expected to reach a maximum towards the end of this linear phase. All the relatively fast-growing plantations species such as those of *Pinus*, *Eucalyptus* and *Acacia* clearly achieved their maximum C stocks at an earlier age (i.e. by around 30 years of age) than the slow-growing *Tectona grandis* (Figure 2), which reached its maximum only after 40 years of age.

Age-wise distributions of different species also reflected the changing preferences over time in species selection for reforestation/afforestation programmes, with the preference for *Pinus caribaea* changing to preference for *Eucalyptus* and *Acacia* species.

Comparison of monoculture C stocks with individual site-specific values reported in literature

Table 18 shows a comparison of the ranges of monoculture C stocks estimated from the present study (Tables 4 – 11) with a variety of site-specific values reported in literature for the major plantation forest tree species found in Sri Lanka. Overall, the majority of site-specific C stock values reported in literature fell within the range of C stock values reported in the present study. For *Pinus caribaea* and *Eucalyptus camaldulensis*, all site-specific values were within the range of C stocks reported in this study. In *E. grandis*, the C stock value reported by Nissanka and Ariyaratne (2003) was 16% greater than the highest per ha C stock value estimated in the present study. However, the estimate by Nissanka and Ariyaratne (2003) is a highly site-specific value for a small area in a location in the up-country Wet Zone (i.e. Anfield Estate, Hatton), based on measurements from small plots (i.e. 20 m x 20 m), and hence cannot be considered as representative of per ha C stock levels of *E. grandis* over extensive areas. On the other hand, there were some extremely low C stock values reported from literature (DeBell *et al.*, 1985; Rockwood & Dippon, 1989; Hunter, 2001). This was primarily because of the younger age of these individual plantations. In *Tectona grandis*, all site-specific values were within the range of C stocks observed in the present study, with the exception of the estimate of Pérez Cordero and Kanninen (2003a, b), which was 7% higher than the highest observed. In *Swietenia macrophylla*, two of the site-specific values (Kawahara *et al.*, 1981; Racelis, 2000) were around 30% greater than the highest per ha C stock observed in the present study, probably indicating better growing conditions and plantation management in those specific sites as compared to those in the Kurunegala district, which contains about 89% of *Swietenia macrophylla* plantation area (Table 9). The majority of site-specific C stock values reported from literature in Table 18 are from the Philippines. However, site and plantation details are not available for these to elucidate possible reasons for their deviations from the per ha C stock estimates of the present study.

Table 18: Comparison of carbon stocks of major plantation forest tree species calculated from the present study with those available in literature

Species	Range of C stocks estimated in the present study (mean C stock) (t C ha^{-1})	C stock value reported in literature (t C ha^{-1})	Remarks	References
Pinus caribaea	31.95 – 204.79 (130.19)	80.62 (AG)†	15 year old stand in Nigeria	Kadeba (1991)
		103.5 (AG)	10 year old stand in Nigeria	Egunjobi & Bada (1979)
		125.6 (AG)	20 year old stand in Northern Nigeria, Based on wood density of 346 kg m^{-3} (Barnes *et al*., 1977) Mature plantation in the Knuckles region, Sri Lanka	Adegbehin *et al*. (1988)
		99.3 ± 5.1 (AG)	Mid-country Wet Zone (WM3b)	Dharmaparakrama (2006)
		76.2 ± 13.3 (AG)	Mid-country Intermediate Zone (IM1b)	Dharamaparakrama (2006)
		63.8 ± 7.1 (AG)	Up-country Intermediate Zone (IU1) 25 year old stand in Lower Hantana, Peradeniya, Sri Lanka	Dharamaparakrama (2006)
		97 (AG)		Ambagahaduwa *et al*. (2009)
		115.5 (AG)		Dharmaparakrama (2006)
		68.5 (AG)	10 year old stand in Nigeria	Poggiani (1985)
Eucalyptus grandis	72.97 – 196.95 (132.72)	197 (AG)	27 year old stand in New South Wales, Australia	Turner & Lambert (1983)
		137 (AG)	12 year old stand in New South Wales, Australia under intensive N, P and K fertilizer treatment	Birk & Turner (1992)
		35	2 year old stand in Florida, USA	Rockwood & Dippon (1989)
		18.8 (AG)	5 ½ year old stand in Hawaii	DeBell *et al*. (1985)
		22.65 (Total)	3 year old stand in Southern India	Hunter (2001)
		234.51 (Total)	19 year old stand in Hatton, Sri Lanka	Nissanka and Ariyaratne (2003)
		53.5 – 70.5 (AG)	5 ½ year old stand in Brazil	Stape *et al*. (2008)

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continued from page 36 –

Species	Range of C stocks estimated in the present study (mean C stock) (t C ha^{-1})	C stock value reported in literature (t C ha^{-1})	Remarks	References
Eucalyptus camaldulensis	11.81 – 43.04 (26.25)	13.45 – 17.55 (Total)	3 ½ year old stand in Southern Brazil	Bernado *et al*. (1998)
		22.65 (Total)	3 year old stand in Southern India	Hunter (2001)
		11.2 – 35.2 (AG)	10 year old *Eucalyptus* plantations including *E. camaldulensis* in New South Wales, Australia	Walsh *et al*. (2008)
Tectona grandis	11.85 – 131.72 (42.70)	70.65 (AG)	15 year old stand in Nigeria	Mbaekwe & Mackenzie (2008)
		120 (Total)	20 year old stand in Panama	Kraenzel *et al*. (2003a)
		142 (AG)	47 year old stand in Costa Rica	Pérez Cordero & Kanninen (2003a)
		113 – 191 (Total)	Mature stand in South-Western Nigeria	Ola-Adams (1993)
		63.38 (AG)	6 year old stand in Costa Rica, Based on wood density of 365 kg m^{-3} (Pérez Cordero & Kanninen, 2003b)	Víquez & Pérez (2003)
		70.65 (AG)	14 year old stand in Nigeria	Mbaekwe & Mackenzie (2008)
		34.2 (AG)	Philippines	Lasco *et al*. (2000)
Swietenia macrophylla	82.67 – 106.49 (97.59)	130.5 (AG)	16 year old stand in the Philippines	Kawahara *et al*. (1981)
		133.76 (Total)	Mature stands in the Philippines	Racelis (2000).
		61.87 (AG)	59 year old stand in Puerto Rico, Based on wood density of 650 kg m^{-3} (Fearnside, 1997)	Wadsworth *et al*. (2003)
		7.7 (AG)	Philippines	Lasco *et al*. (2000)
Acacia mangium	52.54 – 166.32 (110.67)	45.2 (AG)	4 year old stand in Malaysia	Tsai (1988)
		88.1 (AG)	Philippines	Lasco & Pulhin (2003)
		25.6 (AG)	Philippines	Buante (1997), Lasco (2001)
Acacia auriculiformis	79.39 – 93.08 (87.14)	76.8 (AG)	Philippines	Lasco *et al*. (2000)
		28.6 (AG)	Philippines	Buante (1997), Lasco (2001)
		3.3 – 20.7 (AG)	Philippines	Sakurai *et al*. (1994)

†Carbon content in biomass is assumed as 50% in all values.
AG: Above-ground C stock; Total: Total C stock.

CONCLUSION

Carbon stock values calculated in the present study can be considered as the first overall estimates of carbon stocks in the Sri Lankan forest plantations. Despite their approximate nature, these first estimates can be used as basic data in policy formulation on climate change mitigation. These estimates can be fine tuned and made more accurate by updating the FORDATA database, increasing the frequency of measurements of DBH and height and by developing allometric relationships for plantation forest species for which they are not available.

Furthermore, it should be noted that the present study has estimated only the C stock present in the live biomass of forest trees in the respective plantations. However, the total C stock in a forest plantation includes the C stocks in the soil and the understorey vegetation. Therefore, C stock estimates of the present study may be considered as the lower-boundary estimates. More in-depth studies are required to quantify those components of the total C stock in a forest plantation, which were not quantified in the present study. Our estimates also indicated that forest biomass production and C stocks are related to the environmental conditions of the respective sites and regions. Hence, relationships need to be established between biomass production of different forest types and prevailing environmental conditions. These can be either empirical relationships or process-based models, which will enable prediction of the impacts of future climate change on the C stocks of forest plantations in Sri Lanka.

This study highlights the importance of ground-based, on-site measurements of tree dimensions and biomass. Although such measurements are time- and labour-intensive, they are essential to validate the more extensive methods of C stock estimation such as those using remote-sensing. Therefore, ground-based measurement of forest C stocks should be improved and continued and infra-structure facilities for these measurements need to be strengthened.

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